FINAL REPORT

Part 1 - Summary Details

Cotton CRC Project Number: 4.02.09

Project Title: Agronomic management to optimise textile performance

Project Commencement Date: 01/07/2009 **Project Completion Date:** 30/06/2012

CRC Program: The Product

Part 2 – Contact Details

Administrator: Ms Jo Cain (Administration Manager)
Organisation: CSIRO Plant Industry
Postal Address: Locked Bag 59 Narrabri NSW 2390
Ph: 0267991500 **Fax:** 0267931186 **E-mail:** Jo.Cain.csiro.au

Principal Researchers: Dr Michael Bange (Senior Principal Research Scientist) /Dr Robert Long (Research Scientist)
Organisation: CSIRO
Postal Address: Locked Bag 59 Narrabri NSW 2390
Ph: 0267991500 **Fax:** 0267931186 **E-mail:** Michael.Bange@csiro.au; Robert.Long@csiro.au

Supervisors: Dr Greg Constable, Dr Stuart Gordon
Organisation: CSIRO
Postal Address: Locked Bag 59 Narrabri NSW 2390
Ph: 0267991500 **Fax:** 0267931186 **E-mail:** Greg.Constable@csiro.au
Stuart.Gordon@csiro.au

Signature of Research Provider Representative: _____

Project Background

Australian cotton is purchased for a premium as it meets spinner's requirements on the basis of quality and consistency. Coarse (high micronaire) fibre, high nep counts and excessive short fibre content are aspects of Australian cotton that spinners would like to see improved. Fibre quality in the field is affected by a large number of interacting factors: variety, seasonal conditions, crop and harvest management. This project continues explicit and important research employing a combination of both in-field and post-harvest research efforts to improve the quality of Australian cotton, key strategies of both the CRDC and CRC. Improving the understanding of the links between agronomy and textile performance will allow us to better refine in-field crop management recommendations to ensure cotton produced meets or exceeds market expectations.

The previous project 'Linking farming systems with textile performance' successfully assessed the textile performance of current Australian cotton varieties providing valuable feedback to cotton breeders; established better understanding of the influences of crop size, boll load and temperature on micronaire; assessed effects of early defoliation on nep production; and developed a micro-spinning methodology providing a cost effective process to assess the effects of management and future varieties on textile performance.

The knowledge generated from this and the previous project will help to provide management guidelines to growers that will seek to reduce neps and improve consistency of cotton from the field; gain improved knowledge of the effects of environmental and crop stress on micronaire and it components of fineness and maturity; develop guidelines that establish the value of in-field blending/or segregation of harvested lint based on quality attributes; and elucidate other key properties of Australian cotton that may exploited to maintain marketing advantages.

Project Aims and Objectives

This project aimed to optimise cotton fibre quality and enhance the commercial value of Australian cotton through research into direct influences of on-farm agronomic management and climate on fibre development; and post-harvest research that investigates the degree of these influences on textile performance in the mill.

Specific objectives were to: (i) Improve the understanding of the effects of crop stress on micronaire and its components fineness and maturity. (ii) Reduce neps in the field through development of monitoring approaches to identify instances where crops have an increased risk of neps. (iii) Identify management practices that improve the consistency of cotton taken from the field. (iv) Conduct desktop and field research to establish the value (price and textile value) of blending/segregation of lint quality based on quality attributes. (v) Identify other unique fibre quality attributes of Australian cotton to enhance its market value. (vi) Maintain research capability and activities into fibre quality research from the 'field to fabric' that seek to realise outcomes that meet strategic objectives of both CRDC and the CRC.

Table 1: Project objectives and milestones are summarised in the table below:

Objective	**Milestone**	**Performance Indicator**	**Achieved**
Measure effects of crop management on micronaire and its components fineness and maturity and their impacts on textile performance	Complete micro-spinning and fabric manufacturing at Geelong of cotton collected from field studies that compared sowing time, plant size, boll load variety and their interactions.	Cotton processed and fabric manufactured. Results analysed and documented.	✓ Results have analysed and publication is being prepared.
	Undertake experiments that distinguish the relative importance of stress (boll load, temperature, water stress) on fibre micronaire, fineness and maturity.	Complete two glasshouse experiments with growth parameters and fibre samples collected.	✓ In lieu of glasshouse experiments two field experiments were conducted. First year results have been compiled and analysed. Second experiment was undertaken in 2011/2012 cotton season.
Further understand and elucidate fibre properties that affect variation in yarn and fabric quality.	Using a representative sub-set of samples from the above trials conduct wide scale and in-depth testing of fibre, yarn and fabric attributes in order to further elucidate the variation in yarn and fabric quality caused by fibre and spinning properties.	In-depth and comprehensive analysis completed of fibre, yarn and fabric quality and appraisal of variation attributable to fibre and spinning properties	✓ New insights on the use of fibre ribbon width and single fibre strength affecting yarn quality were developed.
Develop in-field management practices to improve consistency of Australian cotton	End-of-season management strategies to ensure consistent quality of field grown cotton using alternative end of season management practices (late season pix, defoliation and irrigation changes) designed and validated.	Completed two field experiments across two seasons, results analysed and documented.	✓
	Complete AFIS, CottonScan and SiroMAT tests for neps, fineness and maturity as well as micro-spinning and fabric manufacturing of cotton collected from field studies.	Cotton processed and fabric manufactured. Results analysed and documented. Guidelines published as an extension article.	✓ Results have been analysed and publication is being prepared.
Assess the opportunities for in-field blending or segregation of lint to improve fibre quality	Undertake studies that consider the benefits of segregation of lint quality in the field for improving value and overall quality for textile production. Future precision	Provide results that can be used to investigate the relative cost/benefits for segregation of lint based on quality to improve growers returns and improved textile production	✓

	agriculture technology may facilitate this approach.		
Communicate results of studies to scientific community and industry	Publish articles and participate in conference and/or industry presentations	2 journal articles, 2 cottongrower articles, at least one major industry presentation per year, participation in fibre to fabric course.	✓
	Update FIBREpak guidelines and BMP information with knowledge developed in this project	BMP guidelines aligned to information provided in FIBREpak	✓

Project Methodology

This project created new knowledge and solutions to challenges associated with Australian fibre quality by:

(i) Undertaking field research that uses alternative end of season management practices to improve the consistency of fibre quality. Practices include the use of late season pix (growth regulator), changes in defoliation and last irrigation timing and plant type/variety. (ii) Conducting experiments to measure and quantify the effects of plant stress with management on micronaire and its components of fineness and maturity. Treatments will vary boll load, temperature and water stress. This research will have relevance to climate change effects on fibre quality. (iii) Initiating studies that consider benefits (both from economic and textile perspectives) of in-field segregation or blending of lint based on fibre quality. The segregation may occur in-field or at the gin. Future precision agriculture technologies as well as new harvesting technologies (producing small round bales) may facilitate these approaches. We will determine economic and textile performance thresholds for segregation and use this information to design a field research program to evaluate potential benefits. Field studies will involve planting varieties with different fibre quality in layouts that will allow cotton to be harvested to enable segregation or blending of the lint. From all experiments yield, plant mapping, and fibre quality (using HVI, AFIS, CottonScan (fineness) and SiroMat (maturity)) was measured. Samples taken from some experiments were also assessed for suitability in spinning using micro-spinning. In addition sub-sets of samples from the field were used to conduct wide scale and in-depth testing of fibre, yarn and fabric attributes in order to further elucidate the variation in yarn and fabric quality caused by differences in fibre and spinning properties. This may include measuring novel fibre quality parameters such as single fibre tensile properties.

This project was the epitome of collaboration in joining field experiments in cotton producing areas with fibre quality measurement and science of spinning technology in Geelong. Collaboration was maintained with other research and breeding on fibre quality to ensure information feeds into research on optimised management strategies for future cotton systems on-farm and post farm gate. Specifically this project supported an experienced technical officer (Jane Caton) in Narrabri working with Dr Bange to conduct field experiments, as well as research scientist Dr Rob Long based in Geelong to undertake post harvest assessments.

Project Results and Outcomes

Results and outcomes from this project are summarised below under the major headings associated with specific project objectives. Where research has been published the appropriate reference in the list of publications is given.

Develop understanding of the degree of management and environmental impacts on micronaire

In recent years spinners have complained about the high micronaire, short fibre and high neps of Australian cotton. A series of warm dry seasons coupled with intensive management for high yield of high retention crops such as Bollgard II® has led to many circumstances of high micronaire. Analysis has indicated that management, varieties and high temperature have been significant components of that result (Kelly et al. 2006). The balance between boll load and crop canopy size can be significant, with high boll loads having lower micronaire (more desirable in this case), presumably from competition (Brook, Hearn and Kelly, 1992; Kelly, Bange and Constable, 2006).

Micronaire is definitely a complex trait, but management can help to address the problem. A variety with inherently lower micronaire (preferably fine and mature) is required. Our research hypothesis is that to achieve mid range micronaire (3.8 - 4.5) should include: crop management to optimise agronomic inputs such as water and fertilizer; utilise growth regulators to manage vegetative growth in balance with boll setting pattern; using a variety with appropriate plant type for the region and climate; and sowing on the appropriate date for

the variety and climate to avoid boll filling of early crops in hotter periods or late crops in cooler periods.Management packages tailored to optimise micronaire across regions and specific climates are required. This part of the project aimed to develop better understanding to what degree fibre micronaire can be manipulated in different climates and by management. This information will help develop management strategies that can help meet fibre micronaire (fibre maturity/fineness) targets.

Temperature Impacts on Micronaire

A journal article describing a new approach for predicting seasonal effects on micronaire was published in the 'Journal of Cotton Science'. We have used this knowledge in the development of fibre quality routines in the OZCOT crop simulation model and are considering a dynamic web tool on the CottASSIST website. Briefly the approach used existing data from sowing time experiments in Australia that spanned three decades, linear responses of micronaire to both daily average and minimum temperatures were developed (r^2 =0.68 for both) (Figure 1). These responses coupled with an estimate of temperature during the boll filling period where the majority of bolls were undergoing fibre thickening were able to successfully predict the micronaire on an independent dataset (r^2=0.41, see Figure 2) despite no account for other climate and management factors that may influence crop micronaire. The ability to predict temperature effects on micronaire will be useful to assess reasons for seasonal and regional differences in micronaire and assess opportunities to modify micronaire with changes in management practices that influence the timing of boll development (see example Figure 3).

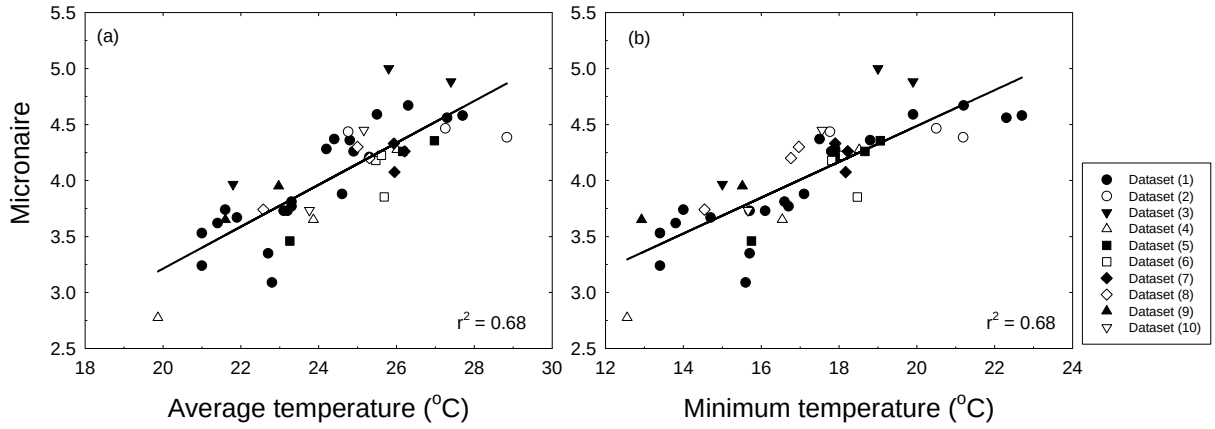

Figure 1: The response of micronaire measured in sowing time studies to (a) daily average temperature and (b) daily minimum temperature during boll filling.

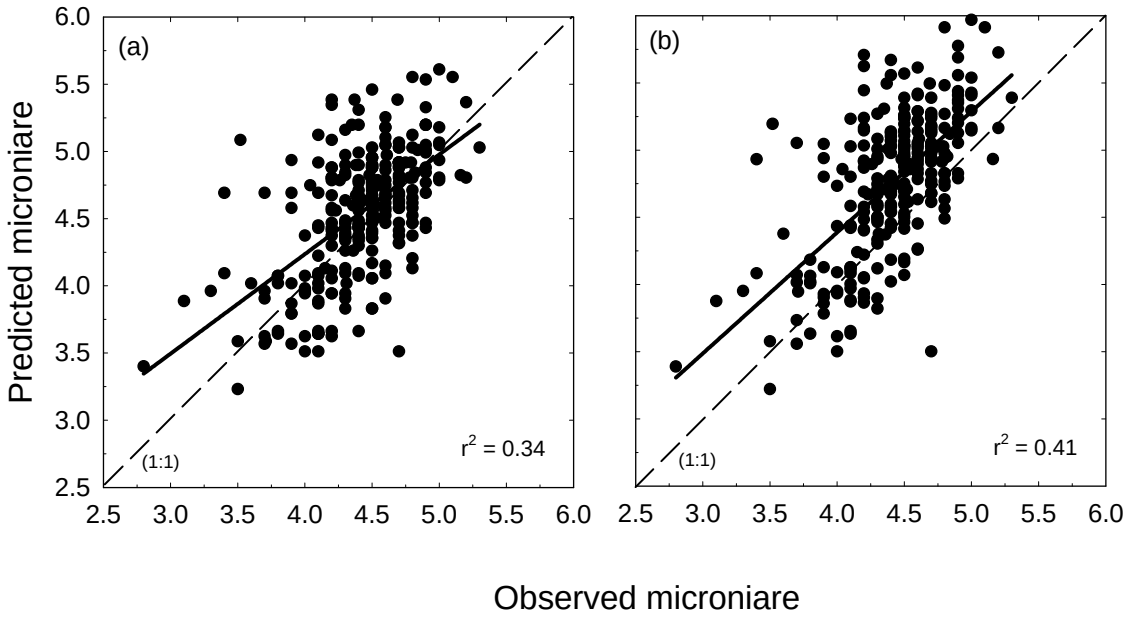

Figure 2: Predicted micronaire versus observed micronaire for the fibre thickening period using Cotton Seed Distributor's (CSD) dataset: (a) micronaire estimated using the linear response of micronaire to daily average temperature un-adjusted for cultivar differences; (b) micronaire estimated using the same response adjusted for cultivar differences. Solid line is the line of best fit. Dashed line is the 1:1 line. (n = 270).

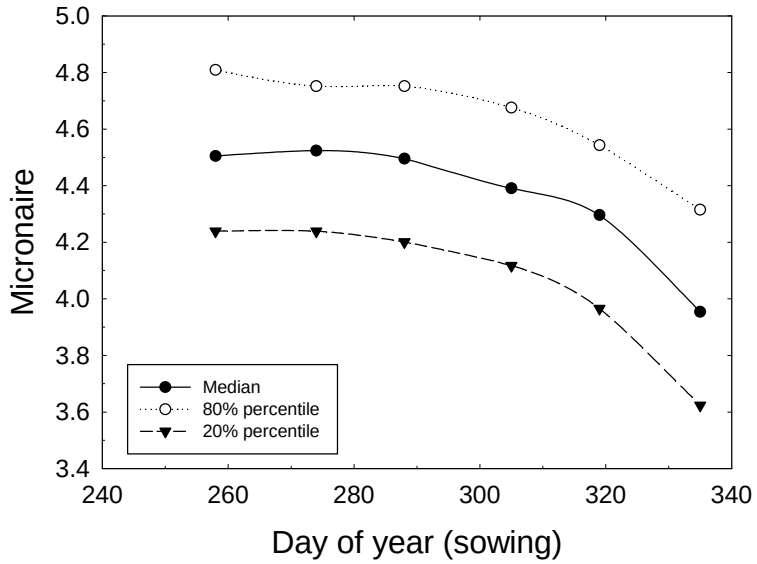

Figure 3: An example of the use of micronaire predictive capability detailed in this paper to assess the impact on sowing time for Narrabri, NSW, Australia. The micronaire prediction uses the daily average temperature. The median and percentiles are calculated from micronaire predictions for 120 years of temperature data.

Micronaire is a measure of cotton fibre quality that is obtained from differences in pressure when air is passed through an accurately weighed plug of cotton fibres. The method measures specific surface area and reflects a combination of the sample's linear density and fibre maturity. A reduction in linear density, wall thickness, or fibre perimeter decreases the micronaire reading as there are more fibres in the plug of cotton increasing air resistance. Low micronaire may indicate the presence of immature fibre while high micronaire may indicate that fibre is coarse. Both situations are problematic for spinners and fabric manufacturers. The optimum micronaire where cotton growers are not penalised ranges from 3.8 to 4.5 (no units).

Fibre growth and development is affected by most factors which influence plant growth. Since the fibre is primarily cellulose, any influence on plant photosynthesis and production of carbohydrate will have a similar influence on fibre growth. Fibre thickening which influences micronaire is affected by temperature and radiation, with large reductions in fibre thickening at lower temperatures or cloudy weather. Boll load and crop canopy also affect micronaire, with high boll loads having lower micronaire, presumably from internal competition. Little research has been conducted attempting to develop an integrated understanding at a canopy level of these impacts on micronaire. This research aimed to provide additional knowledge on the degree of impacts of planting time, cultivar, canopy manipulation, and fruit load on micronaire.

Methods

A field experiment was conducted at Narrabri NSW Australia in the 2008-2009 using cultivars Sicot 70BRF (average micronaire 4.2) and Sicot 71BR (average micronaire 4.7) grown with high input management and insect control. A split plot design with four replicates and 8 m long by 3 m wide (3 rows) plots were used. Main plots were two planting times (16 Oct. (P1) and 14 Nov. 2008 (P2)), and sub plots were a factorial combination of two cultivars, two fruit removal treatments (fruit removed and retained), and three canopy manipulations (tipped, normal, and regulated). Fruit removal was achieved by sequentially removing every second fruit (square, flower or boll) from every plant in 3m by 3m in the plot starting from the bottom of the plant. Fruit were removed at the start of the estimated fibre thickening period (116 days after planting (DAP) in P1 and 104 DAP in P2) based on methodology of described in the previous section on temperature effects on micronaire in this report. Canopy manipulation was undertaken as an attempt to generate differences in canopy size (leaf area index (LAI) by pinching out the terminal with curved forceps to promote extra vegetative growth, or using mepiquat chloride (growth regulant) to restrict vegetative growth. Terminal removal was conducted around the appearance of first square (56 DAP in P1 and 55 DAP in P2), while the growth regulant was applied around the appearance of first flower (84 DAP in P1 and 82 DAP in P2). Growth regulant was also applied after fruit removal to prevent additional vegetative growth.

At the start of the estimated fibre thickening period LAI was measured only on the fruit retained treatment by taking $1m^2$ of plants from within the centre row, removing leaf and measuring leaf area using a Licor (LI-300) leaf area meter. At harvest the number of open bolls in $1m^2$ in each plot was undertaken to determine final boll number (bolls/m^2) and lint was collected from these open bolls to calculate final boll weight (g seed cotton/boll). At harvest (28 May 2009) lint was collected from $1m^2$ and kept for yield and fibre quality analyses. Fibre micronaire measurements on ginned lint samples were performed using a high volume instrument (HVI). Meteorological data for the experimental period were collected 2 km from the field site.

Results

At the time of when the fibre thickening period was occurring, both average daily temperature and solar radiation were declining. The initiation of the fibre thickening phase for P2 was 22 d later than P2 (Figure 4). Average temperature for the fibre thickening phase was 25.4 for P1 and 23.8^{o}C for P2, while average daily radiation was 24.8 for P1 and 22.6 MJ/m^2 for P2.

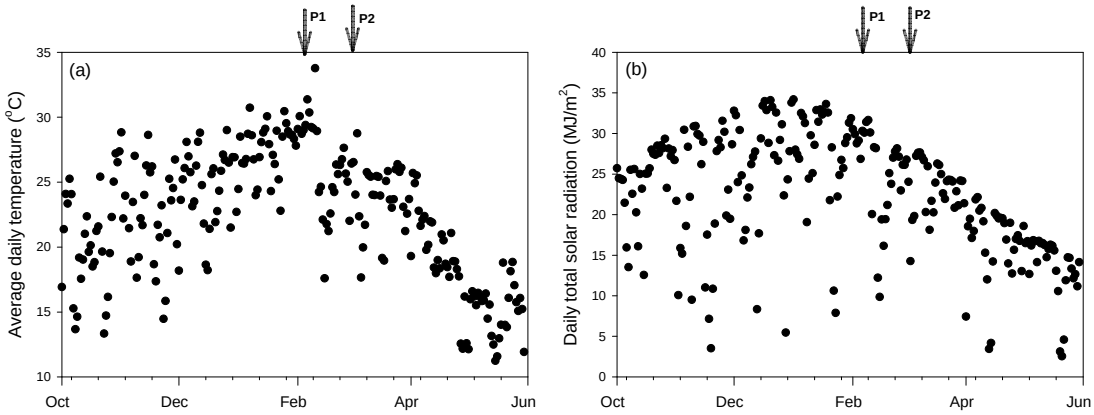

Figure 4. (a) Average daily temperature and (b) daily solar radiation conditions experienced during the experiment. The arrows designate the estimated initiation of the period of fibre thickening. (P1 – first planting, P2 –second planting).

Final boll number was also affected by all treatments (Table 2). Significant interactions were measured for planting time, canopy manipulation, with fruit treatment and for planting time, fruit treatment and cultivar. No significant differences in boll numbers were found among canopy manipulation treatments for the fruit removal treatments, however in the fruit retained treatments across the canopy treatment there were some differences with the normal canopy in P2 with fruit retained recording the highest (mean 144 bolls). When comparing varieties Sicot 70BRF in P1 with fruit retained had similar low boll numbers to the fruit removal of both varieties in P1. The only main effect that was consistent across treatments was the fruit removal treatment with the fruit removal treatment (mean 90) resulting in less bolls than the fruit retained treatment (mean 124).

LAI was only significantly affected by planting time (mean P1 2.29, mean P2 3.06 – Table 2). Significant interactions were also measured for final boll size. An interaction for planting time, canopy manipulation with fruit treatments resulted in considerable combinations of these treatments contributing to differences in boll size. The interaction of fruit treatment and cultivar resulted in Sicot 70BRF with fruit removed having the same boll size as Sicot 71BR with fruit retained and vice versa.

Changes in planting time, cultivar, canopy manipulation, and fruit removal all affected fibre micronaire (Table 2). A significant interaction of planting time, fruit treatment, and canopy size was also measured. Treatments that produced the lowest micronaire were P2 treatments with a canopy that the terminal removed (tipped) with fruit retained or removed. Highest micronaire was measured P1 treatments in normal and regulated canopies with their fruit retained. Across all treatment the only main effects that were consistent were cultivar and planting time. Micronaire of cultivar Sicot 70BRF (mean 4.01) was lower than Sicot 71BR (mean 4.35), while P2 (mean 3.94) had lower micronaire than P1 (mean 4.42).

Table 2. Effect of planting time, canopy manipulation (tipped (T), normal (N) regulated (R)), fruit removal, and cultivar on micronaire, boll number at harvest, and final boll size. Only significant main effects and highest order interactions are shown. LAI at flowering was only measured in the fruit retained treatments.

Variable	Planting	Canopy Size	Fruit Removed		Fruit Retained	
			Sicot 70BRF	Sicot 71BR	Sicot 70BRF	Sicot 71BR
Micronaire	1	T	4.00	4.60	4.35	4.50
		N	3.78	4.38	4.43	4.88
		R	4.05	4.58	4.68	4.83
	2	T	3.60	4.03	3.60	3.63
		N	4.05	4.35	3.80	4.03
		R	3.93	4.33	3.90	4.10
LSD (0.05)	Planting (P)				0.09***	
	Canopy Manipulation (C)				0.10***	
	Fruit Treatment (FT)				0.09*	
	Cultivar (V)				0.09***	
	P x C x FT				0.21*	
Boll Number (/m^2)	1	T	104	89	124	133
		N	92	90	118	103
		R	85	101	106	130
	2	T	89	89	123	118
		N	74	82	132	156
		R	91	91	125	121
	Fruit Treatment				7***	
	P x C x FT				18*	
	P x FT x V				26*	
LAI	1	T	-	-	2.33	2.41
		N	-	-	2.52	2.11
		R	-	-	2.52	1.87
	2	T	-	-	3.10	3.22
		N	-	-	2.85	3.18
		R	-	-	2.84	3.14
LSD (0.05)	Planting				0.40***	
Boll Size (g/ seed cotton/boll)	1	T	4.5		4.9	
		N	4.4		4.7	
		R	4.7		4.8	
	2	T	4.5		4.8	
		N	5.1		5.1	
		R	5.1		5.2	
LSD (0.05)	Canopy Manipulation				0.14***	
	FT x V				0.16***	
	P x C x FT				0.28*	

* Significant at the 0.05 level;** Significant at the 0.01 level;*** Significant at the 0.001 level

Discussion

Management effects were able to generate significant differences in micronaire however, only planting time and cultivar effects were consistent. Lower micronaire with the later planting was a result of lower temperature and radiation. Other studies have shown significant decline in micronaire with later plantings in Australia and this has been associated with lower temperatures. Pettigrew (1995) demonstrated that lower radiation also lowered micronaire on boll cohorts. As expected the cultivar Sicot 70BRF was lower than Sicot 71BR, although the difference was on average less than differences generated by planting time.

Treatments to manipulate the canopy were not successful in changing the LAI (source) at the start of the fibre thickening period. In most instances the only effect of canopy manipulation was the delay in crop maturity caused by the tipped treatment. The delay in maturity (5 d) associated with this treatment would have exposed more bolls to lower temperatures and radiation lowering micronaire similar to that reported by Brook et al. (1992).

The removal of fruit in an attempt to increase the source to sink ratio did not increase micronaire of the remaining bolls. In fact there were more instances where treatments that had fruit retained had higher micronaire. The most likely reason for this is that the removal delayed maturity (again 5 d later) and allowed new bolls to develop later in the season and lowering the overall final micronaire. At harvest there was 27% less bolls than the fruit retained treatments, compared to 50% removal (at treatment implementation) thus indicating new boll development. The micronaire result differed from Brook et al. (1992) where continuous and ongoing removal of fruit generated increased micronaire. Kelly et al. (2006) who compiled cultivar performance data across sites and seasons, and Pettigrew (1995) assessing boll cohorts were also able to generate increased micronaire. In all these cases however, substantially greater reductions in bolls than those implemented in this study were needed to increase micronaire by a small amount.

Treatments in this study were able to generate significant variation in boll number and boll size. Correlation analysis showed that there was a significant ($P < 0.05$) positive correlation of boll size with micronaire (r=0.60). Brook et al. (1992) in their study found a similar response and suggested that an increase in carbohydrate supply to bolls should result in increased micronaire. They also showed that boll size was negatively related to boll number, and in some instances reductions in boll number allowed increases in boll size (and micronaire) when crop maturity was delayed. This suggested that there were compensatory mechanisms affecting these responses. In this study there was no significant correlation of boll number with boll size across all data however, boll size of the later planted (P2), tipped, and fruit removed treatment was similar to the equivalent earlier planted (P1) treatment, and boll size of P2 in other canopy treatments were larger than the equivalent P1 treatments that were the late planted and had fruit removed. Of these treatments the effect translated into lower micronaire for tipped canopies and was similar for the normal and regulated canopies. This suggested a similar response to that of Brook et al. (1992).

Conclusion

This study has highlighted that in capturing understanding of management impacts on micronaire differences in cultivars, and influences of management on the period in which fibre thickening occurs need to be especially considered. It also reinforced opportunities to account for impacts of crop sink dynamics on micronaire by coupling these effects to boll growth directly. Further research is needed to generate larger differences in source/sink dynamics and impacts on micronaire.

Effects of Planting Time, Boll Load and Water Stress on Micronaire

Following on from the experiments described above, a further field experiment was conducted at ACRI to investigate the effects of boll load, temperature and water stress on micronaire. A field experiments was conducted in preference to glasshouse experiments. The experiment consisted of: three sowing times; water stressed and non-stressed treatments applied during boll filling; and fruit removed and non-fruit removed treatments similar to the method described above.

Preliminary analysis showed that there were only main effects on yield (Table 3), with the water stress treatment, later sowings and 50% fruit removal significantly lowering yield. For micronaire the only main effect was sowing time, with lower micronaire measured with later sowings. A significant interaction was determined for the water treatment with sowing time, and for the fruit treatment with sowing time (Table 3). Fruit removal only raised micronaire in the November sowing and not in the others. The most interesting result however, was that the higher micronaire was recorded in the water stressed treatment in the Nov. and Dec. sowings when compared to the non-stress treatment for these same sowings. This result was unexpected as water stress is generally considered to lower micronaire. Final boll number measured at harvest did not explain the result. It may have been expected that water stress could have caused fruit shedding lowering boll number thus leading to an increase in micronaire. Further analysis of results (including fruit retention) is needed to understand the reasons for these results. In addition this experiment was repeated in the 2011/12 cotton season, however at the time this report was being prepared the crop was not harvested.

Table 3. Summary of significant differences of experiment attempting to quantify the impacts of temperature (sowing time), boll load, water stress and the interactions on fibre micronaire.

Treatment	Lint Yield	Final Boll No.	Micronaire
Water Treatment (Stressed/ Non Stressed)	**	n.s.	n.s.
Sowing Time (Early Oct./ Early Nov./Early Dec.)	***	**	***
Fruit Treatment (50% fruit removed/ No fruit removed)	***	***	n.s.
Water Treatment x Sowing time	n.s.	n.s.	**
Water Treatment x Fruit Treatment	n.s.	n.s.	n.s.
Sowing time x Fruit Treatment	n.s.	**	*
Water Treatment x Fruit Treatment x Sowing time	n.s.	n.s.	n.s.

*significantly different 0.05 level, ** significantly different 0.01 level, *** significantly different 0.001 level.

Future work will involve combining data collected from all sites and years once fibre quality analyses (including fibre maturity with Cottonscope and linear density/fineness with Cottonscan) are completed. Results will then be published in a peer reviewed articles. This knowledge will also help in the development of a fibre quality routine for the OZCOT crop simulation model that will predict influences of changes in management and effects of climate change/variability.

End of Season Management to Ensure Consistency of Quality

Effects of End of Season Irrigation, Cutout applications of Mepiquat Chloride, and Early Defoliation

Cotton fibre maturity is an important property to spinners and fabric manufactures as it affects fibre processing from both a physical and chemical perspective. Significant amounts of immature fibre: have little or no secondary wall thickening; is associated with the formation of neps; causes irregularities in yarn; leads to non-uniform dyeing of fabrics; and decreases processing efficiencies. Our research hypothesis was that to minimise immature fibre without sacrificing significant yield we could employ management practices that could cease crop growth and reduce the incidence of immature bolls and thus immature fibre. Practices in this study that were evaluated that cease growth and minimise immature bolls included an earlier defoliation, a cutout rate of mepiquat chloride (pix), and modifying the timing of the last irrigation or missing it altogether. These practices were evaluated on a normal growing crop and on a crop that had been manipulated to establish conditions where there was a larger than normal number of immature bolls. We completed three seasons of experiments in which these management practices were evaluated. All samples were analysed with HVI, AFIS, Cottonscan, Laserscan and SiroMAT.

Results of yield, yield components, and fibre quality attributes showed that there was no treatment that led to improvements in consistency in fibre quality (Table 4). The table below summarises the effects of the growth regulator and early defoliation treatment effects. Overall across the variable it showed that the growth regular had very little effect, while the early defoliation lowered the quality. Despite significant removal of a number of fruiting branches (five removed) there was no evidence that this had an effect on overall quality and quality was not improved with management. Missing the last irrigation also did not have any significant effect on any variable. Further results of textile production are being compiled ready for publication.

Table 4: Summary of results of studies investigating means to improve the consistency of fibre quality. Results presented here are a result of a combined analysis of 3 years. Means presented with similar letters are not significantly different.

Treatment/variable	Control	Growth Regulator	Early Defoliation	Lsd (P = 0.05)
Lint yield (kg ha^{-1})	3008^{a}	2856^{b}	2708^{c}	119
Boll number (m^{-2})	n.s.	n.s.	n.s.	-
DAS 60% bolls open	171^{a}	170^{a}	166^{b}	2.5
Fibre length (mm)	31.57^{a}	31.26 ^{b}	31.28^{b}	0.25
Length uniformity index	84.9^{a}	84.2^{b}	83.7^{b}	0.5
Short fibre index	7.3^{b}	7.7^{ab}	8.0^{a}	0.4
Fibre strength (cN tex^{-1})	n.s.	n.s.	n.s.	-
Fibre elongation (%)	6.3^{b}	6.2^{b}	6.4^{a}	0.1
Micronaire	4.1^{a}	4.1^{a}	3.9^{b}	0.1
Fibre linear density (mtex)	189.4^{a}	190.0^{a}	176.6^{b}	3.6
Fibre linear density SD	n.s.	n.s.	n.s.	-
Maturity ratio	0.91^{a}	0.92 ^{a}	0.87^{b}	0.02
Ribbon width (µmv)	14.42^{a}	14.44 ^{a}	14.34^{b}	0.06
Ribbon width SD	n.s.	n.s.	n.s.	-
Neps (count g^{-1})	195.9^{b}	209.8^{b}	286.7^{a}	39.9
Trash content (count g^{-1})	n.s.	n.s.	n.s.	-

Prediction of End of Season Fibre Quality following Defoliation

We investigated whether the quality of bolls harvested at the time of harvest aid application relates to final quality. There may be an opportunity to use this information to make informed decision on defoliation timing to influence fibre quality. We have published this research in the Agronomy Journal (Bange, M.P. and Long, R.L. (2011)). The abstract for the paper follows:

'To optimize yield and fibre quality, boll cutting is used by cotton (*Gossypium hirsutum* L.) managers to determine when crops are mature and ready for chemical harvest aid application. While it is accepted that the maturity of bolls is defined using seed coat colour, we found no investigations of this definition on overall crop fibre quality. Three field experiments were undertaken in different seasons that systematically varied the timing of harvest aid application to vary the amount of immature, mature, and open bolls to assess (i) fibre quality of open, mature, and immature bolls; (ii) the variation that exists within and across seasons; and (iii) if quality at the time of harvest aid application of immature, mature, and open bolls is related to final micronaire. Within seasons, quality varied by up to 1.06 to 1.53 for micronaire, 0.13 to 0.14 for maturity ratio, and 28.2 to 30.7 μg m−1 for linear density among immature, mature, and open bolls. When data were combined across all seasons relationships were developed that predicted micronaire at harvest using micronaire ($r^2 > 0.73$) and its components together (maturity and linear density) ($r^2 > 0.81$) of the immature bolls measured at harvest aid application (see Figure 5). Relationships were improved when percent open bolls was included as a factor in the regressions ($r^2 > 0.88$). The ability to estimate harvest aid timing influences on micronaire may help avoid discounts. This concept requires more testing with multiple cultivars and would be enhanced with access to reliable and simple methods to measure quality of small field samples.'

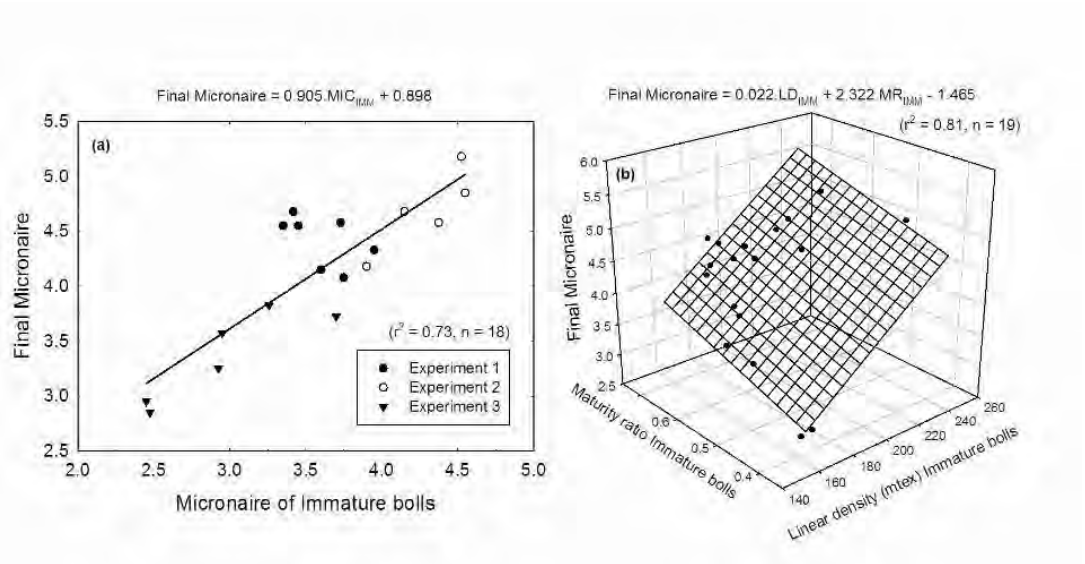

Figure 5. Cotton micronaire at harvest regressed on (a) micronaire of immature bolls (MIC_{IMM}) and (b) linear density (LD_{IMM}) and maturity ratio (MR_{IMM}) of immature bolls measured at the time of harvest aid application. Regressions are fitted to data taken from all experiments combined.

Impact of Fibre Linear Density and Machine Picking on Neps

We utilised fibre quality samples collected from experiments investigating the effects of harvest aid timing on fibre maturity and neps. Handpicked samples prior to picking were compared to samples following machine picking in each of the harvest aid treatments. As far as we are aware this is the first study that has investigated the combined effects of picking and differences in fibre linear density resulting from harvest aid timing. We have submitted a manuscript to the Textile Research Journal (Bange, M.P. and Long, R.L. (2012)) for consideration. The abstract for the paper follows:

'Neps are fibre entanglements created during the mechanical processing of cotton (*Gossypium hirsutum* L.) and are often associated with immature fibres. Even in small amounts neps can affect textile quality and industry reputations. Mechanical harvesting, lower fibre linear density (fineness), and more immature bolls at harvest, all contribute to neps. However, it is not clear whether differences in fibre linear density or immature bolls at harvest interact with picking method to substantially affect neps. The aim of this study was to compare mechanical spindle and hand picked cotton collected from four field studies with treatments that differed in % immature bolls and fibre linear density at harvest and to test for interactions. By systematically varying the timing of harvest aids to cease crop growth, removing fruiting branches, or both, differences in % immature bolls and fibre linear density were generated. In all studies spindle picking increased neps, but there were no significant interactions with harvest aid or branch removal treatments (see Figure 6). When all measurements of neps were combined across studies there was a significant multiple regression that explained the level of neps with picking method and fibre linear density (R^2=0.66) (see Figure 7). These responses supported the individual season analyses finding no significant interaction of picking method with either variable. Spindle picking increased neps by an average of 53 (count g^{-1}). Knowledge of picking effects will identify reasons for increased neps in some cotton regions and help to refine harvest management strategies. Further investigations will include other genotypes with different fibre quality attributes.'

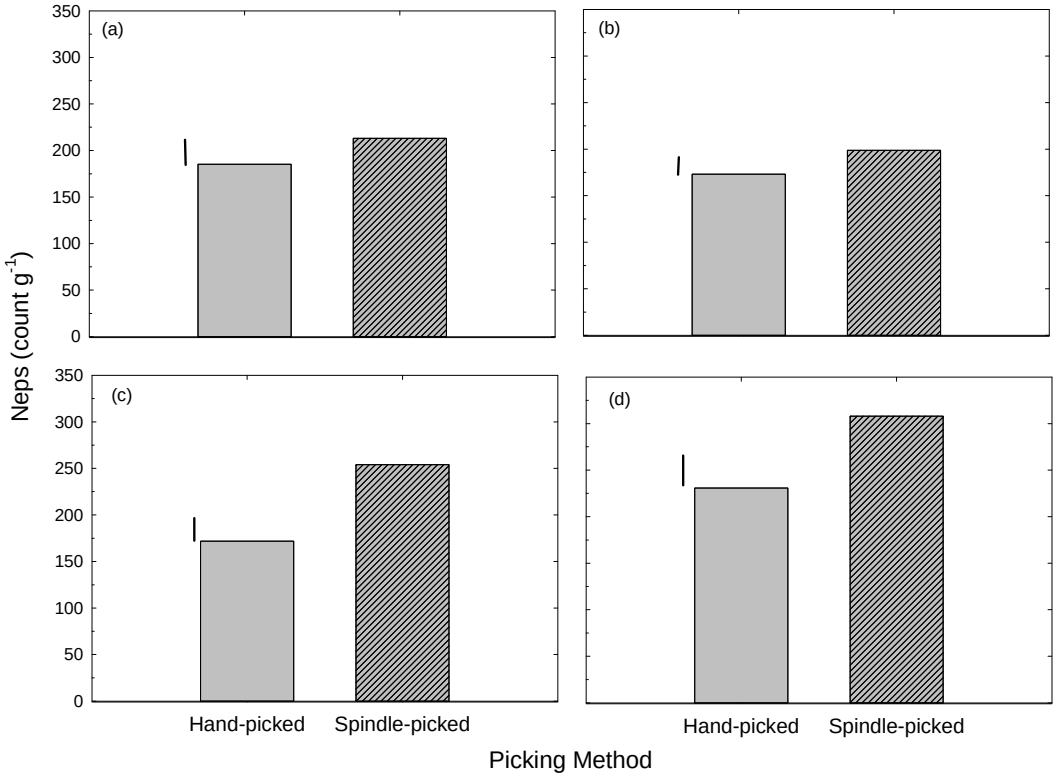

Figure 6. Average impact of picking method on total neps in (a) Experiment 1, (b) Experiment 2, (c) Experiment 3, and (d) Experiment 4. Machine picked cotton refers to spindle picked cotton. The vertical lines represent the LSD of the picking method at $P = 0.05$.

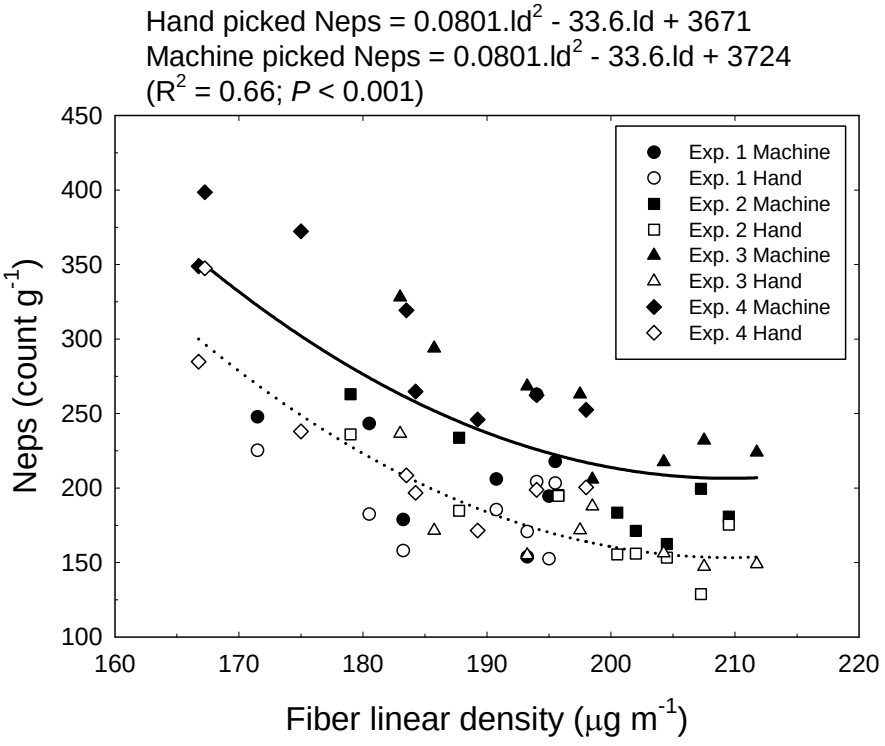

Figure 7. The relationship of fibre linear density (ld) and total neps for handpicked (closed symbols) and machine picked cotton (open symbols). Regressions are fitted to the combined data of all four experiments.

Investigation of strategies for in-field blending of fibre quality

An aspect of blending that has been considered is the potential use of cultivar mixes grown in the field to raise quality without effecting yield. This has been achieved by mixing cultivar seed of varying amounts, or sowing different cultivars in alternative rows and then harvested together. Research on this issue has been undertaken in the USA and has shown at times that yield can be maintained and quality can be improved, but researchers emphasise that this approach is no substitute to raising the overall quality of cultivars sown independently (Bechere et al. 2008; Faircloth et al. 2003). In these studies fibre length, length uniformity, strength and micronaire were all influenced. Other issue highlighted were concerns relating to managing cultivars of varying crop maturity and potential yield reductions resulting from using a cultivar with lower yield.

Current Australian research has been investigating blending from other perspectives; at the mill to reduce costs to the mill while maintaining a quality product; and blending cotton of differing fibre maturity to assess the impact on neps. No studies have specifically been undertaken to quantify blending effects on quality prior to ginning. There is research needed to assess the economic benefits of these concepts, highlight any difficulties associated with processing this cotton (e.g. ginning), and assess the impacts of on textile performance A series of field research and desktop studies will be undertaken to document and demonstrate the value of these approaches. Two field experiments have now been conducted over two seasons at ACRI comparing three cultivars of differing quality and small differences in yield potential. Combination of seed mixtures between cultivars were: 0:100, 25:75, 50:50, 75:25, 100:0. Cultivars obtained from the CSIRO breeding team had inherently different micronaire: Cultivar A (micronaire – 4.6, length – 1.15", strength - 31); Cultivar B (micronaire – 4.2, length – 1.20", strength - 31); Cultivar C (micronaire – 4.2, length – 1.29", strength - 33).

There were no significant differences in yield, strength, and length uniformity in both seasons. The only fibre attribute that was consistently affected across both seasons was fibre length and fibre elongation (Table 5).

Table 5: Summary of significant differences of experiments investigating the effects of blending varieties at sowing time.

Variable	Season	
	2009/10	2010/2011
Lint Yield	n.s.	n.s.
Fibre Length	**	**
Fibre Strength	n.s.	n.s.
Micronaire	*	n.s.
Short Fibre Index	*	n.s.
Uniformity	n.s.	n.s.
Fibre Elongation	**	***

*significantly different 0.05 level, ** significantly different 0.01 level, *** significantly different 0.001 level.

For fibre length in the first season a combination of 25%A with 75%B had a better length than 100% variety A but was not different to 100% variety B. The combination of 25%A with 75%B, and 50%A with 50%B were better than 100%A, but were no better than 100%B. Both 100%B and 100%C were significantly better than 100%A. There were no differences between combination of varieties B and C. In the second season there were fewer

differences, with again the 25%A with 75%B a better length than 100% variety A but was not different to 100% variety B. The combination of 25%A with 75%C, was better than 100%A, and only 100%B was better than 100%A. Again there were no differences between combination of varieties B and C.

For fibre elongation in the first season 100%B and 100%C had lower elongation than 100%A. There were no other differences. In the second season 100%B had a lower elongation compared to 100%A however, 100%C this time was greater than 100%A. In addition 100%C, and 25%B with 75%C had better elongation than 100%B.

It is intended that all results be compiled and analysed and a Cottongrower article written discussing the outcome and for future reference. Outcomes will also be included in the next version of FIBREpak.

Impact of Defoliation on Yarn and Fabric

We again utilised fibre quality samples collected from experiments investigating the effects of harvest aid timing on fibre maturity and neps. Machine picked samples were ginned in Narrabri and sent to CSIRO CSME in Geelong to be processed in yarn and fabric. Again as far as we are aware this is the first study that has attempted to quantify the effects of defoliation timing directly with textile performance. A manuscript detailing the results was published in Field Crops Research (Long, R.L. and Bange, M.P.. (2011). The abstract for the paper follows:

Immature cotton fibre will negatively impact textile processing. Three field experiments were undertaken that applied chemical harvest aids to upland cotton (*Gossypium hirsutum* L.) crops at varying times with the intention of manipulating the maturity of bolls and fibres. The aim was to quantify the effects of these treatments on the textile performance of the harvested cotton and relate these differences to the status of the crop at the time of treatment application. Although earlier treatments produced less mature fibre that was lower in linear density, yarn and fabric strength was not affected. However less mature cotton from a cooler growing season produced stronger yarns (by 3 cN tex^{-1}) and fabric (by 0.39 N (g m^{-2})$^{-1}$) which was partly attributed to the smaller ribbon width of this fibre affecting more fibre packing density and inter-fibre friction (Figure 8). Yarns made from this immature cotton also contained more neps. Micronaire and linear density were equally well related, and more strongly related than maturity ratio, to dyed fabric colour dimensions, which were greatly influenced by treatments. Percent immature bolls at the time of harvest aid application related well to changes in the degree of fabric blueness (R^2 = 0.89) (Figure 9). Knowing the status of a crop in the final stages of production will help cotton producers and the supply chain to predict some of the processing performance aspects of harvested fibre.

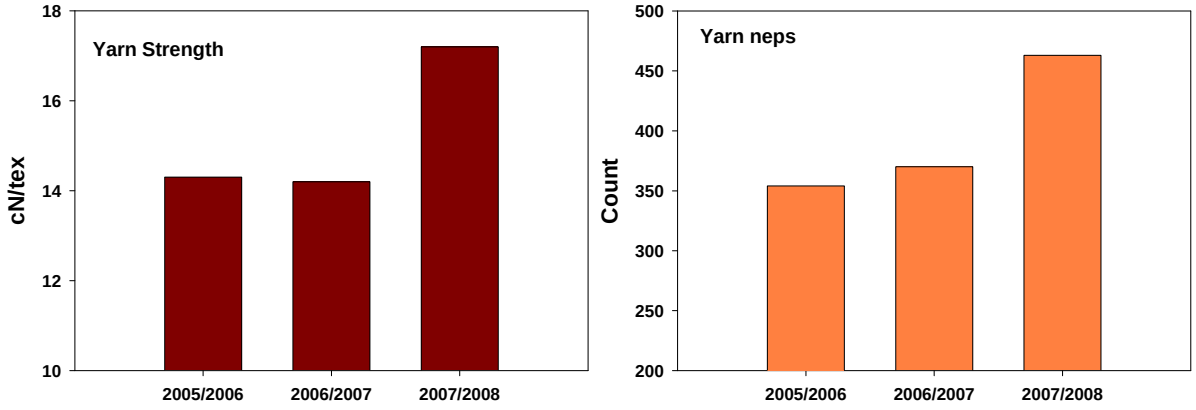

Figure 8. Yarn strength and neps between seasons measured in this study. There were no differences between defoliation treatments in any season.

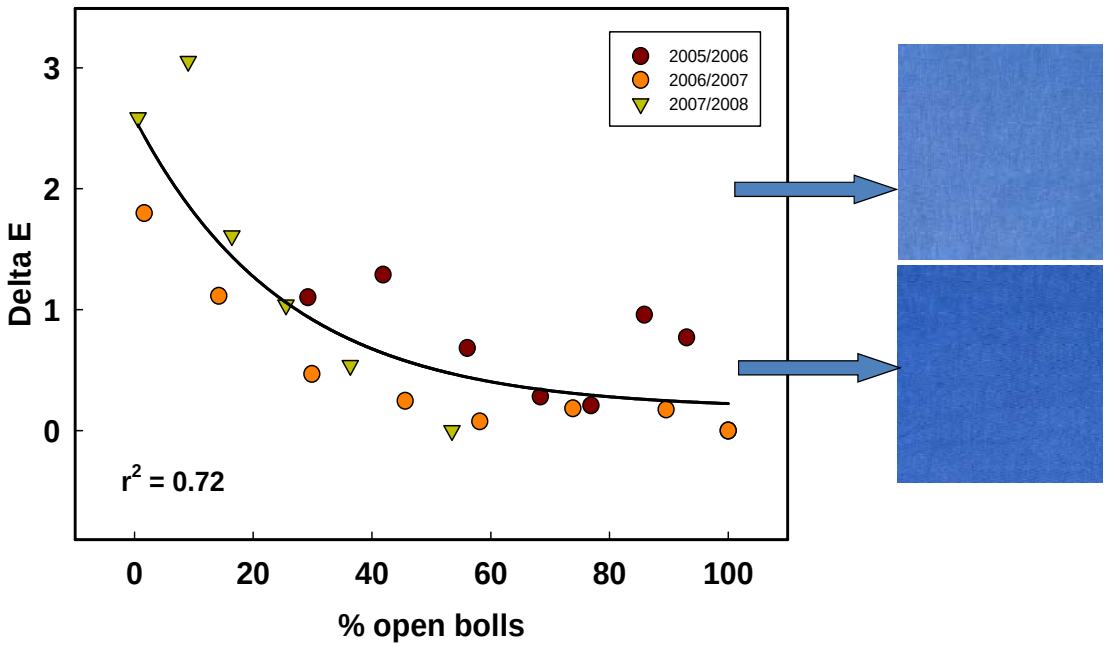

Figure 9. The influence of the timing of defoliation on fabric colour. Delta E values greater than 1 mean that colour changes are visible to the naked eye.

Fibre measurement and yarn strength comparisons of some Australian cotton genotypes

In the previous project 'Linking farming systems with textile performance' a series of large-scale field comparisons of current varieties and breeding lines were undertaken. From these experiments cotton was collected, processed, and sent to Geelong to assess textile performance as well as providing samples as 'test-beds' for investigating novel fibre concepts to help differentiate Aust. fibre. This project continued to process samples from the field experiments and investigated the following:

- Performance of CSIRO varieties and breeding lines in producing premium yarns.
- An assessment of alternative fibre maturity and fineness measurements
- Single fibre strength in describing quality of Australian cotton varieties.
- Development of yarn quality prediction models using existing and alternative fibre quality attributes.

Results of this research are currently being prepared for publication.

Methods

Cultural details of field experiments

Two field experiments comparing different cotton genotypes were conducted over two consecutive growing seasons (2006/ 2007 – Exp. 1 and 2007/ 2008 – Exp. 2) at the Australian Cotton Research Institute (ACRI).

Both experiments employed a randomized complete block design with genotypes as treatments, with two replications. Genotypes used were bred by the CSIRO, and included the commercially available *Gossypium hirsutum* L. (upland) cultivars Sicot 71BR, Sicot 70BRF and Sicala 350B, and the *G. barbadense* L. (pima) cultivar Sipima 280. Experimental upland breeding lines CHQX12B, CHQX377 and CHQX90 were also assessed. Sicot 71BR was the most widely grown Bollgard II®/Roundup Ready® cultivar, and has been popular because of its high yields; in the two seasons encompassing this work Sicot 71BR occupied about 40% of the area grown to cotton in Australia. Sicot 70BRF was only grown in Exp. 2. Sicot 70BRF has a similar genetic background to Sicot 71BR but has the newer Roundup Ready Flex® gene. During the breeding of Sicot 70BRF emphasis was placed on increased fibre length, reduced fibre linear density and improved fibre maturity compared with Sicot 71BR. The other genotypes were included in this study because they also have better fibre quality attributes, e.g. pima has finer and stronger fibres.

Experiments were sown with a disc opening Kinze commercial row-crop planter. Seeds were sown at 5 cm depth, delivered at 15 seeds m^{-1}. Exp. 1 was sown on 17 October 2006, while Exp. 2 was sown on 16 October 2007. Treatment plots were 585 m by 3 rows in Exp. 1 and 175 m by 4 rows in Exp. 2; both had rows spaced at 1 m. Crops were established and grown with full irrigation, and using non-limiting nitrogen applied as anhydrous ammonia (injected below and to the side of the plant line before sowing) at a rate of 180 kg ha^{-1} in Exp. 1 and at a rate of 160 kg ha^{-1} in Exp. 2. Crops were checked regularly for the presence of pests, which were controlled as required according to standard thresholds for non-Bollgard II cotton. Experiments were defoliated in preparation for harvest when all treatments had > 60 % of bolls open (Exp.1, 5 April 2007; Exp. 2, 26 April 2008).

Harvest and ginning

Experiments were machine-harvested with a John Deere spindle cotton picker. Upland seed cotton was ginned on a Continental Eagle 100 saw gin with one lint cleaning passage, located at Cotton Seed Distributors, Wee Waa, New South Wales. Pima cotton was ginned with a Continental Eagle roller gin located at Clyde Agriculture, Bourke, New South Wales.

Fibre quality measurements

HVI testing was undertaken using a Uster Technologies HVI model 1000 located at Auscott Limited, Sydney, New South Wales. Length properties were upper half mean length (mm) which is the average length of the longer half of fibres by weight, length uniformity (%) which is the ratio of the mean length to the upper half mean length, and short fibre content (%) which is an estimate of the percentage of fibres that are shorter than 12.7 mm. Other HVI properties were bundle strength (g tex^{-1}) and elongation (%), and fibre micronaire. HVI results were the average of two replicate tests.

Air flow based linear density [mg 1000 m^{-1} or millitex (mtex)] and maturity (maturity ratio) testing was undertaken at the ACRI using a SDL IIC - Shirley Fineness Maturity Tester (FMT) instrument. Each 10 g fibre sample was cleaned using a SDL HVI Fibre Blender prior to testing. Two replicate tests were made per experimental sample.

Fibre samples (15 to 20 g each) were also subjected to an air driven piston coring instrument to make approximately 300 mg of 2 mm long fibre snippets. Some of these snippets were tested for maturity ratio (birefringence maturity index) using the CSIRO polarized light microscopy instrument SiroMat. Samples were also tested for gravimetrically determined linear density (mtex) using the CSIRO Cottonscan instrument. Snippets were also subjected to fibre diameter (ribbon width) (μm) analysis using the CSIRO photometric laser diffraction based instrument Sirolan-Laserscan; 1000 snippets are assessed per sample replicate. Results presented for polarized light maturity, gravimetric linear density, and ribbon width were the average of three, five and three replicates respectively.

Single fibre strength (cN tex^{-1}) and elongation (%) testing was undertaken with a Textechno Favimat Robot instrument (Textechno, Monchengladbach, Germany) located at the USDA Southern Regional Research Laboratory in New Orleans, Louisiana. Testing was conducted using a 13 mm gauge length, a pre-tension force of 0.85 cN and a cross-head speed of 13 mm min^{-1}. Reported single fibre tensile properties for each experimental unit was an average of no less than 300 single fibre tests.

Fibre cross sectional analysis was conducted at Texas Tech University, Lubbock, Texas. Briefly, a combed fibre sample was embedded in a methacrylate polymer and 1 μm thick fibre cross sections were obtained via a microtome. Slide mounted fibre cross sections were observed with a microscope and captured digital images were analyzed by custom imaging software to measure fibre perimeter, cross sectional area and lumen area; cell wall area is cross sectional area minus lumen area. The degree of secondary wall thickening (fibre maturity, or theta θ) is the ratio of the cell wall area to the area of a circle having the same perimeter as the fibre of interest. Approximately 500 single fibre cross sections were analyzed per test. Cross sectional maturity results were the average of three replicate tests.

Yarn manufacture

Fibre was manufactured into 12 different yarn types at CSIRO Materials Science and Engineering, Belmont, Victoria. For each experimental unit (bale), 50 kg of fibre was opened and cleaned via a Trützschler 'blowroom' which incorporated an Inclined Lattice Bale Feed and CVT3 Opener and Cleaner. The fibre was then carded via a Trützschler DK 903 card and then drawn via one passage of a Trützschler HSR 1000 draw frame. The resulting drawn sliver was then divided into two lots. One lot was subjected to a second draw

frame passage (designated 'card') while the second lot was combed with a Vouk CM 400/S combing machine and then drawn a second time (designated 'comb'). Drawn slivers were converted into twisted roving via a Zinser 660 FU roving machine. Twisted roving was then spun into yarn on a Zinser 350 RM ring spinning machine. Three different yarn weights were manufactured, being 12, 15 and 20 g 1000 m^{-1} (or tex) which correspond to the common yet empirical English cotton count of 49, 39 and 30 Ne yarns, respectively. Each yarn was manufactured at two twist levels, a knitting twist (αe 3.7) and a weaving twist (αe 4.0). Thirty bobbins of yarn were produced for each experimental unit.

Yarn measurements

Yarn was tested for strength (cN tex^{-1}) using a Zellweger Uster Uster Tensorapid 3. Yarn strength is the force required to break the yarn normalized to the linear density of the yarn. Yarn strength results were an average taken from 10 bobbins randomly selected for measurement from the 30 produced.

Data Analysis Yarn Prediction Modeling

Multiple linear regression (MLR) models for yarn strength were developed using the three yarn manufacturing parameters card or comb (numerically designated as either 1 or 2, respectively), yarn count (tex) and yarn twist (turns per meter), and including various combinations of fiber quality attributes. This enabled an uncomplicated yet collective and simultaneous assessment of the yarn performance predictive ability of fiber quality attributes for different yarn types. Individual replicate data for each experiment were used for MLR analysis [Exp. 1 n (number of data points) = 12 (assessed at 12 different yarns n = 144), Exp. 2 n = 14 (assessed at 12 different yarns n = 168)]. The significance of the coefficients determined in each model was assessed at the 5% confidence level using the calculated p-values.

For MLR model performance statistics, the standard error of the estimate (SEE) which is the sum of the residuals divided by the total degrees of freedom was calculated. A lower SEE means that more variation is explained by the model.

A standard error of prediction (SEP) was also determined in a similar manner to the SEE but using the equation determined for one data set to predict the other. For example, data from Exp. 1 was used as a calibration set to develop the model while data from Exp. 2 was used as a validation set.

Performance of CSIRO varieties and breeding lines in producing premium yarns

Yarn strength was different between genotypes, with Sicot 71BR and Sicot 70BRF having equally the weakest yarns while Sipima 280 spun the strongest. CHQX377 had the strongest yarns of the upland genotypes (Table 5). Combed yarns were consistently stronger than carded yarns for all genotypes by an average of 1.4 cN tex^{-1} strength units, although there was significant interaction between genotype for carded and combed yarns; e.g. for Exp. 1 the difference between carded and combed yarns for Sicot 71BR was 1.8 cN tex^{-1} strength units, while the difference for CHQX377 was 1.1 strength units (Table 6). Higher count yarns were consistently stronger, and there was a significant genotype by count interaction for Exp. 1 with 20 tex yarns for CHQX12B being stronger than 15 tex yarns relative to the same difference for the other genotypes. An interaction between the level of twist and yarn count was also captured for both experiments, although it was an additive interaction with low significance; higher (weave) twist yarns were stronger than lower (knit) twist yarns on average by approximately 0.7 cN tex^{-1} strength units (Table 6).

In relation to yarn strength results summarized by the Uster Statistics, Sicot 71BR and Sicot 70BRF were classified in the 78 to 95% level for carded yarns and in the 53 to 95% range for combed yarns. CHQX377 was in the 29 to 54% and 9 to 69% range for carded and combed yarns respectively, while Sipima 280 was in the top 5% group.

Table 6. Yarn strength (cN tex^{-1}) results for genotypes spun into either carded or combed yarns at two levels of twist and at three different counts (12, 15, 20 tex). Significant factorial ANOVA results are reported for both experiments.

	Exp. 1					Exp. 2	
	Genotype x Card Comb		Genotype x Count			Genotype x Card Comb	
Genotype	Card	Comb	12	15	20	Card	Comb
Sicot 71BR	14.6	16.4	14.7	15.6	16.1	14.6	15.9
Sicot 70BRF						14.7	16.7
Sicala 350B	17.6	18.9	17.5	18.2	19.0	16.6	17.5
CHQX12B	16.0	17.6	15.9	16.6	17.8	15.9	16.9
CHQX377	18.8	19.9	18.9	19.3	19.8	18.4	19.2
CHQX90	16.8	18.8	17.2	17.8	18.4	17.0	17.6
Sipima 280	25.1	27.0	25.3	26.1	26.7	25.1	26.4
	LSD = 0.3***		LSD = 0.4*			LSD = 0.3***	

	Count x Twist						Count x Twist					
	Knit twist			Weave twist			Knit twist			Weave twist		
	12	15	20	12	15	20	12	15	20	12	15	20
	17.8	18.6	19.4	18.6	19.3	19.9	17.2	17.5	18.3	17.7	18.5	18.9
	LSD = 0.2*						LSD = 0.2*					

* ANOVA was significant at the 0.05 level
*** ANOVA was significant at the 0.001 level

An assessment of alternative fibre maturity and fineness measurements

There were significant differences between genotypes for fineness and maturity related fibre parameters across both experiments. For micronaire Sipima 280 was lower than the other genotypes while Sicot 71BR had the highest micronaire. CHQX90 had the lowest micronaire of the upland genotypes in Exp. 1 but was equally the lowest with CHQX12B and Sicot 70BRF in Exp. 2. CHQX377 had significantly lower micronaire than Sicala 350B in Exp. 1 but these two genotypes had similar micronaire in Exp. 2 (Table 7).

For either FMT or gravimetrically determined linear density, Sicot 71BR fibre had the highest linear density while Sipima 280 had the lowest. CHQX377 and CHQX90 had similar linear density that was lower than the other upland genotypes (Table 7). Gravimetrically determined linear density values were consistently higher than FMT values by an average of 28 mtex units, and results from these instruments were correlated ($R = 0.90$ and 0.81 including and excluding Sipima 280, respectively, $P < 0.001$).

For FMT determined fibre maturity in Exp. 1 CHQX90 and Sipima 280 were similarly less mature than the other genotypes, while for Exp. 2 CHQX377 and Sicala 350B had higher maturity, with Sipima 280, CHQX90, CHQX12B, Sicot 70BRF and Sicot 71BR having similar maturity (Table 3). For polarized light determined maturity upland genotypes were similar while Sipima 280 was less mature (Table 7). When micronaire and gravimetrically determined linear density were used to calculate maturity values, genotypes were not different for Exp. 1 while in Exp. 2 CHQX377 was higher in maturity with Sipima 280, CHQX12B, Sicot 70BRF and Sicot71BR having lower but similar maturity (Table 3). Cross sectionally determined maturity (theta) results showed no differences in maturity between genotypes in Exp. 1, while for Exp. 2 Sipima 280, Sicala 350B, CHQX377 and Sicot 71BR were similar and more mature than the other genotypes (Table 8).

Polarized maturity values were consistently higher than calculated maturity results by an average of 0.20 units, and polarized determined maturity of upland genotypes was also higher than either FMT or theta maturity ratio results, although Sipima 280 was lower (Tables XX, XX). Relative to theta maturity ratio results FMT maturity had an average absolute difference of 0.05 units, polarized maturity a difference of 0.08 units and calculated maturity ratio was 0.14 units different (Table 7, 8).

The linear relationships between cross sectional theta and either polarized or FMT maturity were not overly strong (i.e. between theta and polarized maturity excluding Sipima 280 $R = 0.56$, $P < 0.01$ and between theta and FMT $R = 0.45$, $P < 0.001$; relationships were insignificantly low when Sipima 280 was included). Calculated maturity ratio values were more strongly correlated with theta measurements ($R = 0.53$, $P < 0.01$; excluding Sipima 280 $R = 0.79$, $P < 0.001$) (data not shown).

The result that polarized light maturity was less for Sipima 280 (the pima genotype) than the other (upland) genotypes is significant (Table 7). Conjecture in regards to the reliability of polarized microscopy determined maturity has typically centered around suggestions that the measurement is confounded by total wall area. It is well known that pima cotton is inherently finer (distinctly smaller fibre perimeter) than upland cotton, ensuring the wall area of pima will be less than an upland genotype regardless of maturity, and thus appearing to have lower polarized determined maturity. Indeed others have reported that polarized maturity ratio was more strongly linearly related to micronaire ($R^2 = 0.88$) than to cross sectionally determined maturity ratio ($R^2 = 0.65$) for the 104 reference bales. Micronaire is practically a surrogate for total wall area, because it too is influenced concurrently by maturity and perimeter.

Laser diffraction determined ribbon width was highest for Sicot 71BR, Sicot 70BRF and CHQX12B, while Sipima 280 had the smallest ribbon width (Table 4). For cross sectionally determined fibre perimeter CHQX12B tended to be larger, while Sipima 280 had the smallest perimeter. CHQX90 and Sipima 280 had smaller total wall areas compared to the other genotypes (Table 8).

Table 7. HVI micronaire and those attributes that are closely related to it: linear density from either FMT or via a gravimetric-imaging instrument (Cottonscan), and maturity ratio measured either via FMT or a polarized light birefringence microscope (Siromat). Maturity ratio was also calculated using the Lord equation (maturity ratio x linear density = 3.86 x micronaire^2 + 18.16 x micronaire + 13) with gravimetrically determined linear density values used therein.

	Micronaire		FMT linear density mtex		FMT maturity ratio		Gravimetric linear density mtex		Polarized light maturity ratio		Calculated maturity ratio	
	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2
Sicot 71BR	4.74	4.45	196	185	0.98	0.95	227	218	1.06	1.01	0.82	0.78
Sicot 70BRF		4.12		168		0.95		207		0.98		0.74
Sicala 350B	4.29	4.27	174	168	0.96	0.98	200	202	1.03	1.01	0.81	0.80
CHQX12B	4.45	4.09	185	173	0.95	0.92	214	208	1.01	0.96	0.80	0.73
CHQX377	4.07	4.25	172	156	0.94	1.01	186	185	1.00	1.00	0.81	0.86
CHQX90	3.64	4.03	160	161	0.87	0.95	180	187	0.96	0.96	0.73	0.80
Sipima 280	3.49	3.43	141	142	0.89	0.91	165	165	0.86	0.87	0.75	0.73
LSD (5 %)	0.28***	0.17***	12***	5***	0.03**	0.04*	12***	9***	0.07**	0.07*	0.08	0.05*

* ANOVA was significant at the 0.05 level
** ANOVA was significant at the 0.01 level
*** ANOVA was significant at the 0.001 level

Table 8. Fibre ribbon width as determined via the laser diffraction instrument Sirolan Laserscan, and cross-sectionally determined fibre perimeter, wall area, and theta (θ) (maturity) which is the ratio of the cell wall area to the area of a circle having the same perimeter as the fibre of interest. Theta was also converted into maturity ratio (maturity ratio = θ / 0.577).

	Ribbon width µm		Perimeter µm		Wall area μm^2		θ		Maturity ratio (from θ)	
	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2
Sicot 71BR	15.2	15.0	49.4	50.8	103.9	106.3	0.55	0.53	0.95	0.92
Sicot 70BRF		14.7		51.4		99.8		0.49		0.85
Sicala 350B	14.4	14.5	48.7	50.5	101.7	107.0	0.55	0.54	0.96	0.93
CHQX12B	15.0	14.9	51.2	53.3	108.5	108.2	0.53	0.49	0.93	0.86
CHQX377	14.0	14.0	47.8	49.2	97.7	104.6	0.55	0.55	0.95	0.96
CHQX90	14.3	14.2	48.4	49.8	93.5	97.3	0.51	0.51	0.89	0.88
Sipima 280	13.8	13.8	45.4	44.8	89.8	84.9	0.56	0.55	0.97	0.95
LSD (5 %)	0.4***	0.3***	2.0**	2.1***	13.4	11.1*	0.07	0.02**	0.12	0.04**

* ANOVA was significant at the 0.05 level
** ANOVA was significant at the 0.01 level
*** ANOVA was significant at the 0.001 level

Single fibre strength in describing quality of Australian cotton varieties

Differences were measured between genotypes for bundle strength and elongation, with Sicot 71BR and Sicot 70BRF having significantly lower strength, while CHQX12B and CHQX377 tended to be the strongest upland genotypes. Sipima 280 had the strongest fibre which was approximately 40% stronger on average than upland genotypes (Table 9). For bundle elongation genotypes ranged from 5 to 7% with Sicot 71BR and CHQX90 having higher elongation compared to the other genotypes (Table 2). Single fibre strength results showed less differences across upland genotypes in Exp. 1, although CHQX377 and Sicala 350B were the strongest upland genotypes in Exp. 2. Sipima 280 was significantly stronger than the other genotypes. For single fibre elongation CHQX12B and Sipima 280 had lower elongation compared to other genotypes which were similar (Table 9).

Bundle strength was on average about 8 g tex^{-1} units higher than single fibre strength (cN tex^{-1} units were converted to g tex^{-1} units for comparisons; 1 cN force = 1.0197 g force). Bundle elongation was on average 1.2 % units less than single fibre elongation. Bundle and single fibre strength measurements were linearly related ($R = 0.94$, $P < 0.001$) although the relationship was not as strong when the potential leverage effects of Sipima 280 were removed ($R = 0.68$, $P < 0.001$) (data not shown). Bundle and single fibre determined elongation were also significantly linearly related albeit not as strongly ($R = 0.67$, $P < 0.001$ with or without Sipima 280). In comparison to other work, Delhom et al. (2010) reported that HVI bundle strength was also higher than Favimat single fibre strength results (single fibre gauge length of 13 mm) by an average (for 8 genotypes) of 7.2 g tex^{-1} units and HVI elongation was 2.3 % units less than single fibre elongation.

Table 9. HVI fibre bundle tensile properties, and Favimat Robot single fibre tensile properties.

	Bundle strength g tex^{-1}		Bundle elongation %		Single fibre strength cN tex^{-1}		Single fibre elongation %	
	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2	Exp.1	Exp. 2
Sicot 71BR	31.9	29.5	7.1	6.8	24.7	22.5	8.1	7.7
Sicot 70BRF		28.9		7.0		21.3		7.7
Sicala 350B	34.1	31.8	6.3	5.9	25.9	24.7	8.0	7.5
CHQX12B	34.7	32.3	5.9	5.8	24.4	22.8	6.3	6.2
CHQX377	35.1	32.8	6.2	6.5	25.2	25.2	7.6	8.2
CHQX90	33.1	31.1	6.6	7.0	22.6	23.4	8.7	8.6
Sipima 280	46.8	46.2	5.7	5.1	33.0	32.6	6.9	7.2
LSD (5 %)	2.0***	0.8***	0.6*	0.8**	4.0*	2.6***	0.6**	0.9*

* ANOVA was significant at the 0.05 level
** ANOVA was significant at the 0.01 level
*** ANOVA was significant at the 0.001 level

Development of yarn quality prediction models using existing and alternative fibre quality attributes

Yarn strength models developed using linear density and maturity ratio variables as an alternative to micronaire performed better than those models using micronaire alone. For example using Exp. 1 data validated against Exp. 2 models, the SEP for the standard model including micronaire was 1.56 compared with better SEP (standard error of prediction) values of 1.10, 1.17 and 1.17 for models using either FMT linear density and maturity, cottonscan gravimetric linear density and polarized maturity ratio, or cottonscan gravimetric linear density and calculated maturity ratio variables, respectively (Table 10).

Models developed using cross sectionally determined fiber perimeter and maturity (theta) parameters in replacement for micronaire performed well and were similar to standard models with micronaire; e.g. for calibrations combining both experiments and using cross sectional parameters R^2 = 0.95, SEE = 0.79, compared with the standard model including micronaire R^2 = 0.95, SEE = 0.81(Table 10).

When laser diffraction determined ribbon width was used as a replacement for micronaire, MLR models consistently performed better than models which used micronaire or other alternatives to micronaire. For example where Exp. 2 data was validated against Exp. 1 models (excluding Sipima 280), the ribbon width model yielded an SEP = 0.99, while other models had inferior SEP values greater than 1.50 (Table 11). Similarly for the combination of data from both experiments, the calibration developed with ribbon width yielded the model with the lowest SEE (0.51) of all the models (Table 1, Fig. 10).

This may be attributed to ribbon width being an attribute that relates to how fibers will best pack together in a yarn. While any measure that helps to define cotton fineness, e.g. micronaire, linear density or cross-sectionally determined perimeter, will be useful, ribbon width may well simply give the best average indication of the fineness or coarseness of fibers regardless of how the external architecture of fibers are influenced by other components such as convolutions, the degree of fullness affected by fiber maturity, and fiber perimeter. Indeed the relationship between ribbon width and cross sectional perimeter was expected to be reasonable but not perfect due to convolutions and fullness effects. This was demonstrated by Adedoyin et al. (2010) who measured the ribbon width of approximately 1000 fibers from each of a selection of 10 of the 104 reference cotton bales and reported a reasonable linear relationship between ribbon width and cross-sectionally determined perimeter (R^2=0.81) (Fig. 11a). For the same 10 samples (as part of a separate subset of the 104 reference cotton bales made available to the CSIRO in 2006), cross-sectional perimeter was slightly more linearly related to Sirolan Laserscan ribbon width (R^2 = 0.89) (Fig. 11a), but not as strongly when all 104 reference cottons were analyzed (excluding 5 missing/ outlier samples n = 99) (R^2 = 0.83) (Fig. 11b). For the data reported herein for the two experiments, the relationship was not as strong (R^2 = 0.53).

Apart from re-confirming the concept of using laser diffraction to measure the diameter of fibers, Adedoyin's work attempted to use the technology specifically for cotton. While Sirolan laserscan has been available commercially since the 1990's, other technology has also been available to measure the width of textile fibers such as the OFDA (BSC Electronics, Australia) which is based on digital image analysis technology which has now been incorporated into Cottonscope. A microscope image determination of ribbon width may well differ to that derived via laser diffraction and which would in turn relate differently to yarn strength data. Quantifying such differences would be an interesting topic of future research.

Models that employed single fiber strength attributes performed better than those using standard HVI bundle tensile properties. For example using Exp. 2 data validated against Exp.

1 models, the SEP for the model including single fiber strength and elongation was 1.04 compared to the standard model SEP of 2.33 (Table 10). Others reported that correlations between fiber strength and yarn strength were improved when single fiber tensile properties were used instead of stelometer or HVI bundle strength parameters. Single fiber testing offers a more direct measure of inherent fiber tensile properties which will thus reflect more directly how fiber tensile properties will affect the tensile properties of yarn. Single fiber testing avoids undesirable effects present in bundle testing such as clamping and alignment issues. Furthermore the number of fibers in a bundle of a given linear density may vary due to differences in individual fibers (e.g. there will be more less mature fibers in a bundle), and this might compound the effects of other bundle testing issues. Nonetheless bundle testing is still a fast, convenient and practical method of determining the tensile properties of cotton fiber. Single fiber testing will be undertaken more readily for research when testing instrumentation like the Favimat Robot becomes more automated.

Table 10. Multiple linear regression statistics for models predicting yarn strength for all genotypes, using data from both experiments used alternately as either the calibration or validation set, including calibration models using data from both experiments. Standard variables included three yarn manufacturing parameters (a numericised designation for card or comb yarns, yarn tex and yarn twist), as well as HVI fibre quality parameters upper half mean length, length uniformity, short fibre content, bundle strength, bundle elongation and micronaire. In addition to the standard variables, some models included alternative maturity and fineness related variables as a substitute for micronaire (†), and single fibre tensile properties as a substitute for bundle tensile properties (‡). Performance statistics are the coefficient of determination (R^2), standard error of the estimate (SEE), and standard error of prediction (SEP).

	Calibration Exp. 1		Validation Exp. 2		Calibration Exp. 2		Validation Exp. 1		Calibration combined Exps.	
	R^2	SEE	R^2	SEP	R^2	SEE	R^2	SEP	R^2	SEE
Standard variables	0.98	0.54	0.93	2.33	0.97	0.62	0.96	1.56	0.95	0.81
†FMT linear density and maturity ratio	0.98	0.53	0.91	2.10	0.97	0.56	0.96	1.10	0.96	0.67
†Gravimetric linear density and polarized maturity ratio	0.98	0.52	0.95	2.15	0.98	0.54	0.97	1.17	0.96	0.70
†Gravimetric linear density and calculated maturity ratio	0.98	0.54	0.94	2.17	0.98	0.55	0.96	1.17	0.96	0.70
†Cross sectional perimeter and theta	0.98	0.49	0.92	2.42	0.98	0.48	0.85	1.60	0.95	0.79
†Ribbon width	0.98	0.48	0.94	1.73	0.97	0.55	0.97	1.18	0.97	0.66
‡Single fiber strength and elongation	0.97	0.65	0.93	1.04	0.97	0.61	0.90	1.34	0.96	0.74

Table 11. Multiple linear regression statistics for models predicting yarn strength for all genotypes excluding Sipima 280. Data from both experiments was used alternately as either a calibration or validation set. Calibration models were also developed using data from both experiments. Variable and performance statistics descriptions are common to the previous table.

	Calibration Exp. 1		Validation Exp. 2		Calibration Exp. 2		Validation Exp. 1		Calibration combined Exps.	
	R^2	SEE	R^2	SEP	R^2	SEE	R^2	SEP	R^2	SEE
Standard variables	0.91	0.53	0.61	1.88	0.81	0.64	0.83	1.25	0.82	0.70
†FMT linear density and maturity ratio	0.94	0.43	0.49	1.80	0.88	0.51	0.79	0.92	0.86	0.62
†Gravimetric linear density and polarized maturity ratio	0.92	0.48	0.73	1.58	0.91	0.44	0.83	0.78	0.90	0.53
†Gravimetric linear density and calculated maturity ratio	0.91	0.52	0.67	1.80	0.89	0.50	0.84	0.78	0.88	0.58
†Cross sectional perimeter and theta	0.94	0.41	0.52	2.02	0.89	0.49	0.53	1.48	0.83	0.67
†Ribbon width	0.94	0.43	0.71	0.99	0.90	0.47	0.88	0.69	0.90	0.51
‡Single fiber strength and elongation	0.91	0.52	0.73	0.90	0.87	0.54	0.72	1.57	0.86	0.61

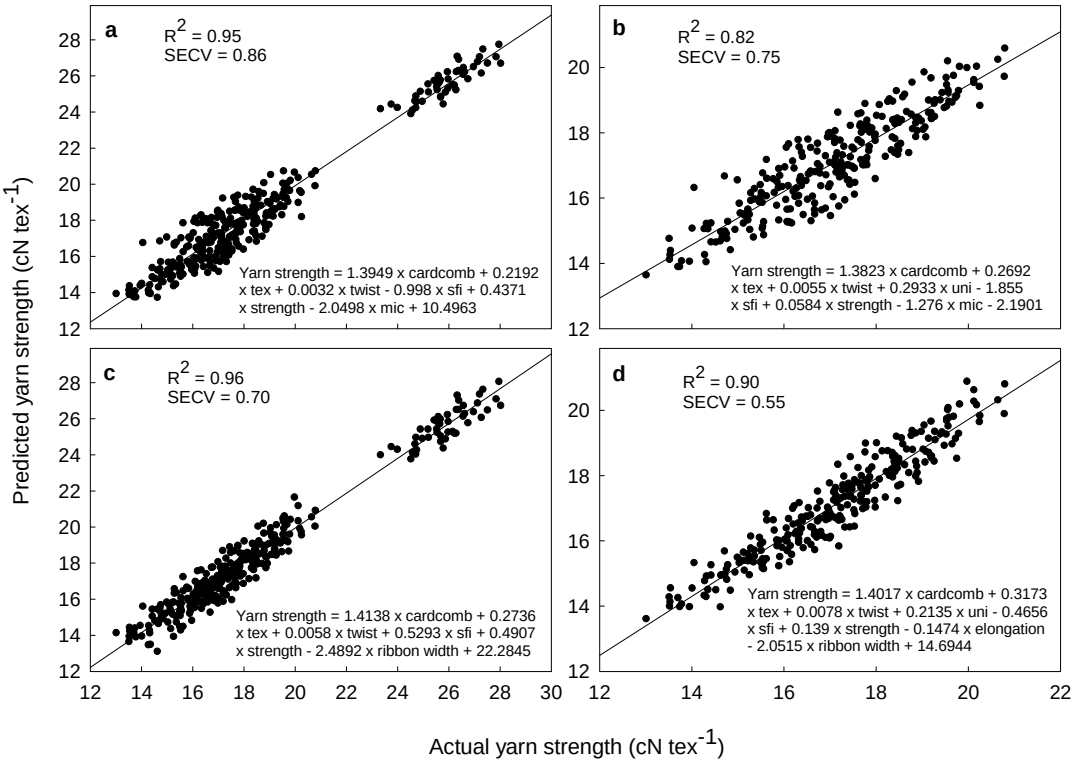

Figure 10. Multiple linear regression calibration models for yarn strength combining data from both experiments including yarn manufacturing parameters and standard HVI fiber quality attributes [length uniformity (uni), short fiber content (sfi), bundle strength and elongation] including (a, b) micronaire and using (c, d) ribbon width in substitution for micronaire. Models were developed with (a, c) all genotype data and (b, d) excluding the potential leverage effects of pima data. Models are those excluding variables that did not statistically contribute to regression performance

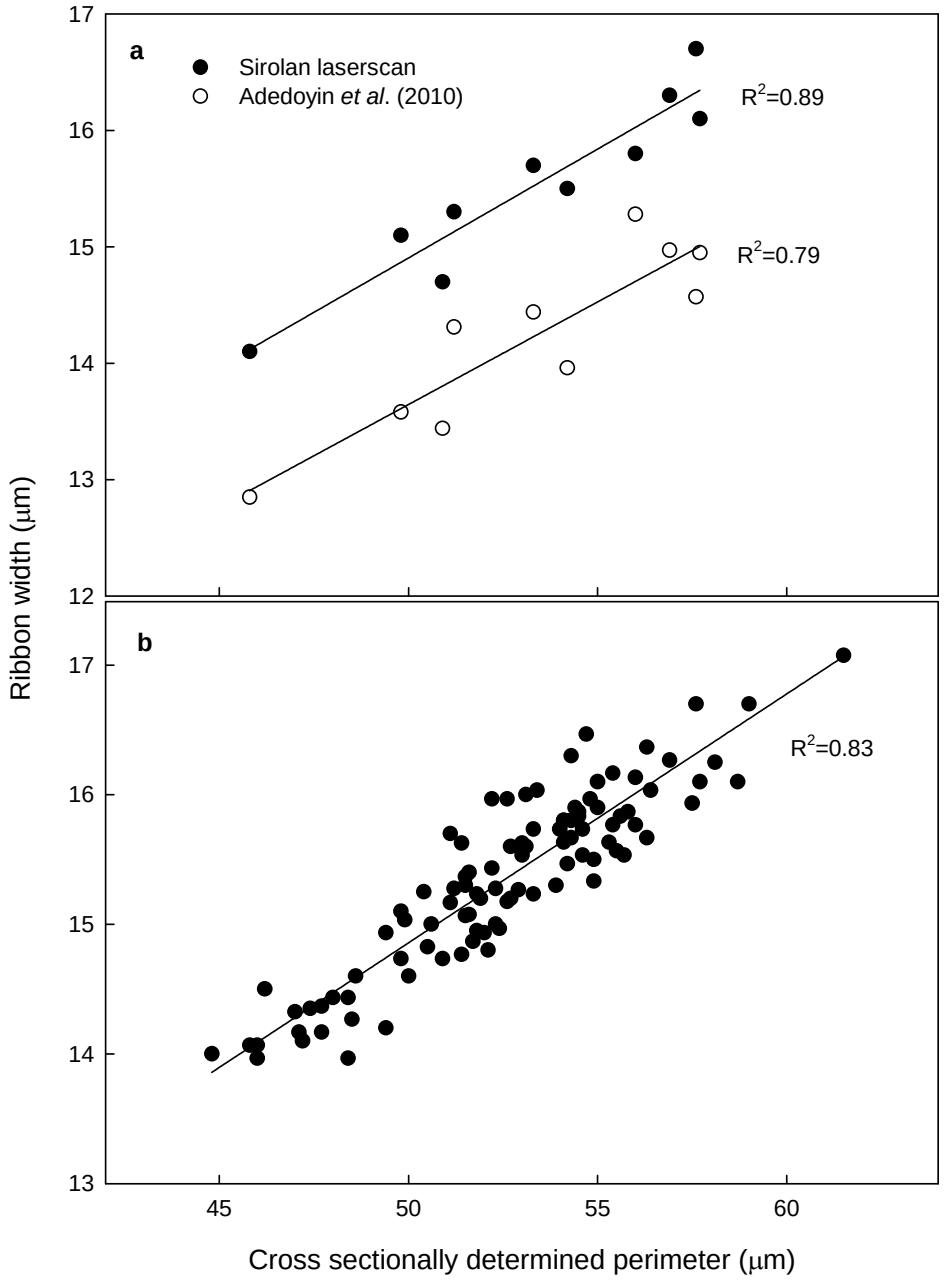

Figure 11. Linear relationships between cross sectionally determined fiber perimeter and laser diffraction determined ribbon width as measured via either a laboratory prototype instrument (data reproduced from Adedoyin et al. (2010)) or by the Sirolan Laserscan. Data were (a) 10 samples selected from the 104 reference set and (b) 99 samples from the same set.

Conclusion

Linking research on crop management with textile performance can be applied to optimise fibre quality. This project was successful in providing new knowledge on fibre quality issues through:

- Research generated in the study was used in the development of FIBREpak, the industry's BMP fibre quality module, and many chapters of the cotton production manual.
- Continued to raise the awareness of the effects of climate and management on fibre quality through the Geelong 'Field to Fabric' course, FIBREpak, and various other industry forums.

- Improved understanding of the changes in crop management practices and climate that affect micronaire and its components of linear density and maturity. Information generated in this project specifically attempted to quantify the effects of management practices that influence boll number, temperature, and water stress on micronaire. A new methodology to predict micronaire using temperature around boll filling was developed. In addition the impacts of various management practices on micronaire were best reflected though boll size rather than boll number. Information is still being compiled to further address these issues.

- A potential in-field approach to estimating the influence of harvest aid timing on final micronaire at harvest was developed by measuring the quality of immature bolls at the prior to the time of harvest aid application. The approach is limited by a simple and cost-effective approach to measuring fibre quality from small samples taken from the field.

- Demonstrated in-field blending of cotton seed attempting to raise quality; no benefits were identified.

- Research was undertaken to assess whether end of season management could be employed to improve the consistency of fibre quality. In these studies no improvements were identified through the use of late season application of Mepiquat Choride, missing last irrigation, or defoliating earlier. Analyses of post-harvest textile measurements are continuing to further assess these approaches.

- The effects of early harvest preparation on fibre immaturity and textile performance was quantified and related to measurements of crop status. Results showed that the current industry recommendation of application of harvest aids at 60% bolls open is adequate to limit impact on yarn strength and dye uptake. The use of ribbon width as measured by the CSIRO Laserscan was useful in explaining outcomes generated in this research.

- For crop maturity manipulating experiments (via defoliation) percent immature bolls at the time of harvest aid application related well to changes in the degree of fabric blueness (R^2=0.89).

- Despite differences in fibre linear density resulting from differences in harvest aid timing at the time of harvest the machine spindle harvesting method however, did not interact with harvest aid timing to further increase neps. Multiple regression analysis was able to show that on average machine spindle harvesting contributed 53 neps (count/g) over hand-harvested cotton

- Multiple linear regression models for yarn strength which included yarn manufacturing variables card or comb, count (12, 15, 20 tex), twist (knit or weave) and HVI fiber quality parameters performed well. Models performed better when alternatives to micronaire, such as gravimetric linear density, were used, although models using laser diffraction ribbon width were best. Ribbon width is thought to provide information about the external architecture of fibers as inclusively influenced by perimeter, maturity and associated fullness effects, and fiber shape, and may thus best depict how fibers will pack together in a yarn and the subsequent relationship to yarn strength.

- Although yarn strength models were good when including HVI bundle tensile properties, models performed better when single fiber tensile properties were used instead. This was attributed to single fiber testing being free of alignment, length variation and variable strain at break effects, all shortfalls seen in the bundle method.

Ongoing on-farm research into fibre quality will be most likely be supported through the ongoing project 'Agronomic Management for Better Fibre and Textile Quality' supported by CSIRO and the CRDC. This new project will continue explicit systems research combining in-field and post-harvest research to improve the quality and value of Aust. cotton. New research will include undertaking the first systems experiments investigating the value of the use of premium varieties with modified 'fibre friendly' agronomy and processing compared with standard practice. Large scale farming systems experiments will compare ± premium varieties, ± modified agronomy (including changes in irrigation, crop cessation and defoliation management)). Field measurements by CPI from Narrabri will include crop maturity, yield, and quality. Seed cotton from these experiments will be delivered to CMSE in Geelong to be ginned using protocols developed for premium fibre and compared to standard practice. Treatments include changes in moisture control (with heating), limiting lint cleaners, adjusting saw speed and comb ratios. Efficiencies in the ginning process will be measured. Using large scale mill processing, lint will be then processed into both carded 20 tex standard yarns and combed 12 tex (or finer) yarns which will be tested for quality attributes and manufactured into finished dyed fabric which will also be tested. As a result of these studies the economic value of various practices for improved yarn and fabric quality can be established.

Other research will include: (1) Developing improved understanding of fibre properties (including the lower limit of fibre fineness) that increase neps in fibre, yarn and fabric. Finer fibres are sought by spinners, but efforts to reduce fineness may increase their propensity to nep. (2) Undertake research to develop an improved understanding of the value of late season bolls to final yield and quality. Techniques will be assessed to help growers determine if there is any value or opportunity in pursuing bolls that have not opened at the end of the season when harvest aid decisions are being made. Research will involve studies monitoring development of individual bolls complemented with a series of demonstration sites in all cotton regions to investigate this issue with grower involvement. (3) Evaluate methods to enable growers and ginners to predict quality at the end of season to assist with harvest preparation and gin settings through online micronaire and neps predictors, and scoping opportunities for in-field measures of quality.

Knowledge generated will be used to update concepts detailed in FIBREpak and myBMP, and provide the basis of future research and incentives to undertake regional investigations and extension to improve fibre quality. Processing information will contribute to the CottonSpec initiative. Importantly the project will continue to provide samples as 'test-beds' for investigating novel fibre concepts of single fibre strength, fibre diameter- ribbon width, surface friction and elongation to help differentiate Aust. fibre.

While the new project will maintain important research capability into fibre quality, it brings together two projects that are fully coordinated and integrated, that have synergy and no duplication. Collaboration with other research and breeding on quality ensures optimised management strategies for future cotton systems on-farm and post farm gate.

Publication List

Refereed Journal Articles

1. Bange, M.P. and Long, R.L. (2011). Optimizing timing of chemical harvest aid application in cotton by predicting its influence on fiber quality. Agronomy Journal 103 (2): 390-395.
2. Bange, M.P., Constable, G.A., Johnston, D.A. and Kelly, D. (2010). A method to estimate the effects of temperature on cotton micronaire. Journal of Cotton Science 14(3):164-172.
3. Bange, M.P., Long, R.L. Constable G.A., and Gordon, S. (2010). Minimizing immature fiber and neps in Upland cotton (*Gossypium hirsutum L.*). Agronomy Journal. 102 (2):781-789.
4. Long, R.L., Bange, M.P. (2011). Consequences of immature fiber on the processing performance of Upland cotton. Field Crops Research. 121:401-407.
5. Long, R., Bange, M., Gordon, S. and Constable, G. (2009). Measuring the maturity ratio of developing cotton fibers using an automated polarised light microscopy technique. Textile Research Journal. 80(5): 463-471.
6. Long, R.L., Bange, M.P., Gordon, S.G., van der Sluijs, M.H.J., Naylor, G.R.S. and Constable, G.A. (2010). Fibre quality and textile performance of some Australian cotton genotypes. Crop Science. 50(4):1509-1518.

Grower Magazine Articles

7. Bange, M.P., and Brodrick, R. (2010). Do sowing rules change for Bollgard II cotton. The Australian Cottongrower. 31(4). pp.11-14.
8. Bange, M.P., and Long, R.L. (2010). The impact of early defoliation on neps. The Australian Cottongrower. 31(4). pp.39-41.
9. Bange, M., Constable, G., Gordon, S., Long, R., Naylor, G., van der Sluijs, R. (2010). Preparing for harvest to preserve fibre quality. Australian Cottongrower. 31(1). pp. 10-14.
10. Bange, M., Constable, G., Gordon, S., Long, R., Naylor, G., van der Sluijs, R. (2010). Pre-sowing considerations to preserve fibre quality. Australian Cottongrower. 31(3). pp. 12-16.
11. Bange, M., Constable, G., Gordon, S., Long, R., Naylor, G., van der Sluijs, R. (2011). In-season considerations to preserve fibre quality. Australian Cottongrower. 31(7). pp. 38-41.
12. Long, R., Bange, M., Gordon, S. and Constable, G. (2010). Measuring the maturity of developing cotton fibres. The Australian Cottongrower 31(7). pp.34-36.
13. Long, R., and Bange, M. (2011). The impact of early defoliation on textile performance. The Australian Cottongrower 32(3). pp.14-18.

Others Publications

14. Bange, M.P. (2010). Introduction. Australian Cotton Production Manual. Cotton Research and Development Corporation and the Cotton Catchment Communities Cooperative Research Centre. p. 4.
15. Bange, M.P. (2010). Dryland cotton potential and risk. Australian Cotton Production Manual. Cotton Research and Development Corporation and the Cotton Catchment Communities Cooperative Research Centre. pp. 8-12.
16. Bange M.P., Constable, G.A., Gordon, S.G., Long, R.L., Naylor, G.R.S. and Van der Sluijs, M.H.J. (2010). Managing for fibre quality. Australian Cotton Production Manual.

Cotton Research and Development Corporation and the Cotton Catchment Communities Cooperative Research Centre. pp. 26-28.

17. Bange M.P., Constable, G.A., Gordon, S.G., Long, R.L., Naylor, G.R.S. and Van der Sluijs, M.H.J. (2010). Ginning. Australian Cotton Production Manual. Cotton Research and Development Corporation and the Cotton Catchment Communities Cooperative Research Centre. pp. 91-92.

Extension and Education Activities

2009/ 2010

- M. Bange presented at the Field to Fabric course in Geelong.
- M. Bange presented to UNE and Sydney University Students on crop physiology including fibre development as part of their excursion to Northern NSW.
- M. Bange gave a lecture at Sydney University on cotton agronomy and physiology including fibre development and management.
- M. Bange gave two web on Wednesday (CSD) presentations.
- M.Bange spoke at the Gwydir Irrigators forum on climate change.
- M.Bange presented to the UNE Cotton Course.
- M.Bange assisted Sandra Deutscher with the development of MyBMP guidelines for in-field management for optimum fibre quality.
- M.Bange assisted with providing information for a campaign targeting neps.
- M.Bange contributed to two CRDC spotlight articles.

2010/2011

- M. Bange presented at the Field to Fabric course in Geelong.
- M. Bange presented to UNE and Sydney University Students on crop physiology including fibre development as part of their excursion to Northern NSW.
- M. Bange gave a lecture at Sydney University on cotton agronomy and physiology including fibre development and management.
- M. Bange presented to the UNE Cotton Course.
- M. Bange assisted Sandra Deutscher with the development of MyBMP guidelines for in-field management for optimum fibre quality.
- M. Bange and R. Long gave a presentation at the Australian Cotton Conference.
- M. Bange and R. Long gave a presentation at the Cotton CRC Conference.
- M. Bange assisted with the development of the Australian Cotton Production Manual.

2011/2012

- M. Bange presented at the Field to Fabric course in Geelong.
- M. Bange presented to UNE and Sydney University Students on crop physiology including fibre development as part of their excursion to Northern NSW.
- M. Bange gave a lecture at Sydney University on cotton agronomy and physiology including fibre development and management.
- M. Bange presented to the UNE Cotton Course.
- M. Bange assisted Sandra Deutscher with the development of MyBMP guidelines for in-field management for optimum fibre quality.
- M. Bange assisted with the development of the latest version of the Australian Cotton Production Manual.
- M. Bange presented at Career Pathways in the Cotton Industry ~ Teacher Professional Development Event (March 2011).
- M. Bange presented at two upper Namoi cotton field days for new growers.
- M. Bange presented at the Macintyre Field Day on fibre quality.
- M. Bange presented at two field days in Griffith during the cotton season.
- M. Bange presented at three workshops on waterlogging effects at Moree and Mungindi.
- M. Bange assisted with numerous CRC cottontales and CSD media (web on Wednesday, facts on Friday).
- M. Bange assisted with the development of the latest version of the Australian Cotton Production Manual.

- M. Bange presented field to fabric course for Schools (September 2011).
- M. Bange contributed to four CRDC spotlight articles (one on Pix and three on fibre quality)
- Michael Bange and Robert Long presented at the CRC Science Forum in 2012.

Final Report Executive Summary

Agronomic management to optimise textile performance

Principal Researchers M.P. Bange, R.L. Long (Researchers)/J. Caton (Technical Officer)
Supervisors G.A. Constable, S.G. Gordon

Australian cotton is purchased for a premium as it meets spinner's requirements on the basis of quality and consistency. Coarse (high micronaire) fibre, high nep counts and excessive short fibre content are aspects of Australian cotton that spinners would like to see improved. Fibre quality in the field is affected by a large number of interacting factors: variety, seasonal conditions, crop and harvest management. This project continues explicit and important research employing a combination of both in-field and post-harvest research efforts to improve the quality of Australian cotton, key strategies of both the CRDC and CRC. Improving the understanding of the links between agronomy and textile performance will allow us to better refine in-field crop management recommendations to ensure cotton produced meets or exceeds market expectations.

Specific objectives were to: (i) Improve the understanding of the effects of crop stress on micronaire and its components fineness and maturity. (ii) Reduce neps in the field through development of monitoring approaches to identify instances where crops have an increased risk of neps. (iii) Identify management practices that improve the consistency of cotton taken from the field. (iv) Conduct research to establish the value (price and textile value) of blending/segregation of lint quality based on quality attributes. (v) Identify other unique fibre quality attributes of Australian cotton to enhance its market value. (vi) Maintain research capability and activities into fibre quality research from the 'field to fabric'.

This project was successful in providing new knowledge on fibre quality issues through:

- Improved understanding of the changes in crop management practices and climate that affect micronaire and its components of linear density and maturity.
- A new methodology to predict micronaire using temperature around boll filling was developed.
- A potential in-field approach to estimating the influence of harvest aid timing on final micronaire at harvest was developed by measuring the quality of immature bolls at the prior to the time of harvest aid application.
- Demonstrated in-field blending of cotton seed attempting to raise quality; no benefits were identified.
- Research was undertaken to assess whether end of season management could be employed to improve the consistency of fibre quality. In these studies no improvements were identified through the use of late season application of Mepiquat Choride, missing last irrigation, or defoliating earlier.
- The effects of early defoliation on fibre immaturity and textile performance was quantified and related to measurements of crop status. Results showed that the current industry recommendation of application of harvest aids at 60% bolls open is adequate to limit impacts on yarn strength and dye uptake.
- Despite differences in micronaire resulting from differences in defoliation timing machine spindle harvesting did not interact with harvest aid timing to further increase neps. On average machine spindle harvesting contributed 53 neps over hand-harvested cotton.
- Multiple linear regression models for yarn strength which included yarn manufacturing variables card or comb, count (12, 15, 20 tex), twist (knit or weave) and HVI fibre quality parameters performed well. Models performed better when alternatives to micronaire, such as gravimetric linear density, were used, although models using laser diffraction ribbon width were best. This information has contributed to the development of Cottonspec.
- Continued to raise the awareness of the effects of climate and management on fibre quality through the Geelong 'Field to Fabric' course, FIBREpak, myBMP, the cotton production manual, and various other industry forums.

Ongoing on-farm research into fibre quality will be most likely be supported through the ongoing project 'Agronomic Management for Better Fibre and Textile Quality' supported by CSIRO and the

CRDC. New research will include undertaking the first systems experiments investigating the value of the use of premium varieties with modified ‘fibre friendly’ agronomy and processing compared with standard practice. Other research will include: Developing improved understanding of fibre properties that increase neps in fibre, yarn and fabric. Finer fibres are sought by spinners, but efforts to reduce fineness may increase their propensity to nep; Undertaking research to develop an improved understanding of the value of late season bolls to final yield and quality; and (3) Evaluating methods to enable growers and ginners to predict quality at the end of season to assist with harvest preparation and gin settings through online micronaire and neps predictors, and scoping opportunities for in-field measures of quality.

.

Optimizing Timing of Chemical Harvest Aid Application in Cotton by Predicting Its Influence on Fiber Quality

Michael P. Bange* and Robert L. Long

ABSTRACT

To optimize yield and fiber quality, boll cutting is used by cotton (*Gossypium hirsutum* L.) managers to determine when crops are mature and ready for chemical harvest aid application. While it is accepted that the maturity of bolls is defined using seed coat color, we found no investigations of this definition on overall crop fiber quality. Three field experiments were undertaken in different seasons that systematically varied the timing of harvest aid application to vary the amount of immature, mature, and open bolls to assess (i) fiber quality of open, mature, and immature bolls; (ii) the variation that exists within and across seasons; and (iii) if quality at the time of harvest aid application of immature, mature, and open bolls is related to final micronaire. Within seasons, quality varied by up to 1.06 to 1.53 for micronaire, 0.13 to 0.14 for maturity ratio, and 28.2 to 30.7 μg m^{-1} for linear density among immature, mature, and open bolls. When data were combined across all seasons relationships were developed that predicted micronaire at harvest using micronaire ($r^2 > 0.73$) and its components together (maturity and linear density) ($r^2 > 0.81$) of the immature bolls measured at harvest aid application. Relationships were improved when percent open bolls was included as a factor in the regressions ($r^2 > 0.88$). The ability to estimate harvest aid timing influences on micronaire may help avoid discounts. This concept requires more testing with multiple cultivars and would be enhanced with access to reliable and simple methods to measure quality of small field samples.

Precise identification of cotton crop maturity is important for maintaining yields and fiber quality when preparing for harvest. Delayed harvest increases the chance of fiber weathering and harvesting more leaf trash, while prematurely harvesting cotton with significant amounts of immature bolls may lower lint yield and micronaire (a measure of fiber fineness and maturity), and increase neps (fiber entanglements) (Bednarz et al., 2002; Bange et al., 2010). Reducing fiber linear density or fiber maturity (i.e., reducing cell wall thickness) can lower micronaire. Methods employed by crop managers to identify when cotton crops are mature and ready for application of harvest aids include monitoring crops to establish when they have reached: 60% open bolls, four nodes above cracked boll (NACB), and the majority of bolls can be defined as mature using the color of the seed coat by cutting bolls open (Bednarz et al., 2002; Faircloth et al., 2004a, 2004b; Kerby et al., 1992; Snipes and Baskin, 1994; Thibodeaux et al., 1993).

Nodes above cracked boll and 60% open bolls are reliable indicators of crop maturity for uniform crops and when they have a regular distribution of bolls (Faircloth et al., 2004a, 2004b). The boll cutting technique is often used in conjunction with these monitoring approaches, and is generally accepted as the most reliable methodology as it directly quantifies percent boll maturity. This was supported in an investigation of timing of harvest aid application by Bange et al. (2010). When a boll is dissected, it is defined as being mature when the seeds contained within the boll are well developed (not gelatinous) and their seed coats have turned dark yellow or brown (Brecke et al., 2001). It is generally recognized that accumulation of cellulose in fibers has ceased when coloration of seed coats is occurring (Leffler, 1987; Stewart, 1987).

While the development and growth of seeds and fiber in individual bolls have been studied in detail (see reviews by Leffler, 1987; Stewart, 1987), we are aware of no reports of fiber quality of bolls classified as mature or immature using the boll cutting technique and how this relates to overall final crop fiber quality.

Three experiments conducted in different seasons that varied the timing of chemical harvest aid application were used to:

1. Assess the fiber quality of mature and immature bolls as defined by the boll cutting technique.
2. Understand the variation in fiber quality associated with the boll cutting technique that exists within and across seasons.
3. Establish whether the fiber quality of bolls defined as immature, mature, or open at different times of assessment relates to final fiber quality.

The fiber quality attributes investigated were micronaire and its components fiber maturity (maturity ratio) and linear density (fineness). Knowledge of these effects will help to refine harvest management strategies to optimize quality.

M.P. Bange, CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW 2390, Australia. R.L. Long, CSIRO Materials Science and Engineering, P.O. Box 21, Belmont, VIC, 3216, Australia. Cotton Catchment Communities Cooperative Research Center. Received 2 July 2010. *Corresponding author (michael.bange@csiro.au).

Published in Agron. J. 103:390–395 (2011)
Published online 10 Jan 2011
doi:10.2134/agronj2010.0293

Abbreviations: CSIRO, Commonwealth Scientific and Industrial Research Organisation; DAS, days after sowing; HVI, Spinlab High Volume Instrument model Classing 900; LD_{IMM}, linear density (μg m^{-1}) of immature bolls; MIC_{IMM}, micronaire of the immature bolls; MR_{IMM}, maturity ratio of the immature bolls; NACB, nodes above cracked boll.

Table 1. Micronaire, maturity ratio, and linear density (fineness) for immature (I), mature (M), and open bolls (O) measured at various % open bolls in Exp. 1 (2005/06) following the application of chemical harvest aid treatments. Harvest aids were: 0.2 L ha^{-1} Dropp Liquid; 3 L ha^{-1} Prep 720; and 2 L ha^{-1} D-C Tron.

Harvest aid treatment	Open bolls	Micronaire				Maturity ratio				Linear density			
		Boll maturity											
		I	M	O	Mean	I	M	O	Mean	I	M	O	Mean
	%									–μg m^{-1}–			
1	29.2	3.75	4.00	4.20	3.98	0.70	0.84	0.86	0.86 c§	181.0	196.0	206.8	146.2 a
2	41.9	3.60	4.75	4.50	4.28	0.71	0.91	0.85	0.85 c	186.7	219.7	212.5	154.9 ab
3	56.0	3.45	4.78	4.63	4.29	0.72	0.78	0.81	0.81 bc	187.5	224.5	224.0	159.2 b
4	68.4	3.35	4.88	4.48	4.24	0.61	0.66	0.64	0.64 a	188.7	218.8	208.5	154.2 ab
5	76.9	3.95	4.98	4.35	4.43	0.70	0.81	0.73	0.73 ab	205.5	221.0	214.2	160.4 b
6	85.9	3.42	4.74	4.70	4.29	0.67	0.78	0.80	0.80 bc	181.5	223.1	223.5	157.2 ab
7	93.0	3.73	4.93	4.63	4.43	0.65	0.90	0.79	0.79 bc	192.9	217.7	214.0	156.4 ab
Mean boll maturity		3.61 a	4.72 b	4.50 b		0.68 a	0.81 b	0.78 b		189.1 a	217.3 b	214.8 b	
LSD‡ harvest aid			ns†				0.09**				12.00*		
LSD boll maturity			0.28***				0.06***				7.91***		
LSD harvest aid × boll maturity			ns				ns				ns		

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† No significant difference at 0.05 level.

‡ LSD calculated at 0.05 level.

§ Harvest aid means in the same column and boll maturity means for each character followed by the same letter are not significantly different at 0.05 level according to LSD.

MATERIALS AND METHODS

Cultural Details and Treatments

Three harvest aid timing field experiments as reported in Bange et al. (2010) were conducted at the Australian Cotton Research Institute at Narrabri (30° S, 150° E). This is a semiarid environment with a uniform gray cracking clay soil (USDA Soil Taxonomy: Typic Haplustert) in northwestern New South Wales, Australia. Experiments 1 and 2 consisted of seven harvest aid application dates with a control which allowed all bolls to fully mature, while Exp. 3 had five applications and a control that was treated 185 days after sowing (DAS) (Tables 1 and 2). Each experiment used a randomized complete block design with four replications.

Treatment plots (8 by 10 m), contained eight rows spaced at 1 m. In the center two rows of each plot, a mixture of leaf defoliant and a boll opener was applied as a harvest aid at approximately 5-d intervals in Exp. 1 and 2, and 7-d intervals in Exp. 3. Initiation of harvest aid treatments in Exp. 1 was at 29% open bolls (143 DAS). In Exp. 2 and 3, an attempt was made to generate treatments with more immature bolls, with the first harvest aid treatment being applied at 1.6% open bolls (136 DAS) in Exp. 2, and at 0.6% open bolls (143 DAS) in Exp. 3.

Harvest aids were sprayed with a calibrated CO_2 pressurized boom with total swath width of 3.0 m using flat fan nozzles (110–01) at 200 k Pa delivering 100 L ha^{-1} of spray solution. The chemical and rates were: 0.2 L ha^{-1} Dropp Liquid (Bayer CropScience, active constituent 500 g L^{-1} Thidiazuron); 3 L ha^{-1} Prep 720 (Bayer CropScience, active constituent 720 g L^{-1} Ethephon); and 2 L ha^{-1} D-C Tron (Caltex, active constituent 991ml L^{-1} Petroleum Oil).

Experiments were sown with a commercial row crop planter (Exp. 1–15 Oct. 2005; Exp. 2–20 Oct. 2006; Exp. 3–16 Oct. 2007) using upland cotton. In Exp. 1 and 2 Bollgard II Roundup Ready (Monsanto) cultivar Sicot 71BR (CSIRO, Australia) was used while Exp. 3 used nontransgenic cultivar Sicot 71 (CSIRO, Australia; Reid, 2003), the recurrent parent of cultivar Sicot 71BR. Both cultivars have normal leaf shape, medium to late maturity and compact growth habit. Typical fiber quality attributes of Sicot 71BR are 29.2 mm fiber length, 31 cN tex^{-1} fiber strength, and micronaire of 4.5. Attributes of Sicot 71 are similar fiber length and fiber strength to Sicot 71BR, and micronaire of 4.4 (Cotton Seed Distributors, 2008). Each experiment was established and grown with full irrigation using nonlimiting N and thorough insect control as described in Hearn and Fitt (1992). Nitrogen was applied as anhydrous ammonia (injected below and to the side of the plant line) 4 wk before sowing at a rate of 200 kg N ha^{-1}. The rate of N was determined on the basis of a N replacement program that accounts for N use in previous cotton crops (Rochester, 2007). Temperature data for the experimental period were measured 2 km from the field site at a fully serviced weather station.

Crop Condition at Harvest Aid Application

To assess crop condition when harvest aid treatments were applied, several measurements were taken on the control plots on each day of treatment application. In a fixed area of 1 m^2 in each control plot, a percentage of open bolls, (defined as when two sutures on the boll had split), was determined. On five plants taken from 0.5 m^2 from the control plots on each day of treatment, all bolls (regardless of size or age) from each plant were removed to determine the number of open, mature, and immature bolls (bolls m^{-2}). Immature bolls were distinguished from mature bolls by cutting bolls perpendicular to their vertical axis and assessing the color of the seed coats within the bolls. A seed coat that was not dark was classified as immature (Brecke et al., 2001). Fiber samples from immature, mature, and open bolls were retained at each harvest aid application date for fiber quality analyses.

Fiber Quality Analyses

Micronaire (no units) of fiber samples was determined using a Spinlab High Volume Instrument (HVI) model Classing 900

Table 2. Micronaire, maturity ratio, and linear density (fineness) for immature (I), mature (M), and open bolls (O) measured at various % open bolls in Exp. 2 (2006/07) and Exp. 3 (2007/2008) following the application of chemical harvest aid treatments. Harvest aids were: 0.2 L ha^{-1} Dropp Liquid; 3 L ha^{-1} Prep 720; and 2 L ha^{-1} D-C Tron.

Harvest aid treatment	Open bolls	Micronaire			Maturity ratio			Linear density		
		Boll maturity								
		I	M	O	I	M	O	I	M	O
	%								–μg m^{-1}–	
Experiment 2										
1	1.6	3.90a§	5.53f	5.01de	0.70cd	0.76de	0.84e	198.5a	238.4fg	242.8g
2	14.2	4.38bc	5.23ef	5.08de	0.68bcd	0.70cd	0.71cde	218.3bcde	237.2efg	239.2g
3	29.9	4.15ab	5.43ef	5.10ef	0.56ab	0.76cde	0.66bcde	205.3ab	245.1g	235.2cdefg
4	45.6	4.55bc	5.23ef	5.10ef	0.64bcd	0.63bcd	0.61bc	217.0abcd	233.3cdefg	236.3defg
5	58.2	4.65cd	–	5.20ef	0.63bcd	0.61bc	0.71cde	235.1cdefg	219.8bcdef	245.1g
6	73.8	–	–	5.18ef	0.47a	0.69bcd	0.64bcd	244.1g	250.3g	244.2g
7	89.5	–	–	5.05de	–	0.72cde	0.71cde	–	216.8abc	232.0cdefg
LSD harvest aid			ns†			0.08**			11.3***	
LSD‡ boll maturity			0.14***			0.05***			7.44***	
LSD harvest aid × boll maturity			0.43**			0.13**			19.3***	
Experiment 3										
1	0.6	2.45a	4.58f	–	0.38a	0.66de	–	164.7ab	207.8 gh	–
2	9.0	2.48a	4.35def	4.71f	0.39a	0.66de	0.67de	161.0a	200.1fgh	209.2h
3	16.4	2.93b	4.08cde	4.65f	0.55bc	0.54b	0.69e	172.5abc	190.0def	213.0h
4	25.5	2.95b	4.08cde	4.43ef	0.57bcd	0.61bcde	0.65cde	162.2ab	188.9def	193.8efg
5	36.3	3.70c	4.00cd	4.33def	0.61bcde	0.65cde	0.61bcde	179.7cde	183.5cde	194.0efg
6	53.5	3.26b	3.88c	4.33def	0.63bcde	0.61bcde	0.69e	180.1cde	176.3bcd	193.7efg
LSD harvest aid			ns			0.06*			ns	
LSD boll maturity			0.17***			0.04***			5.9***	
LSD harvest aid x boll maturity			0.41***			0.10***			14.6***	

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† No significant difference at 0.05 level.

‡ LSD calculated at 0.05 level.

§ Harvest aid ´ boll maturity means (three columns per character) followed by the same letter are not different at 0.05 level according to LSD.

(Zellweger Uster, Knoxville, TN). Some samples however, were too small (<8 g) to be tested by HVI. All samples were then blended through one passage of a SDL "Shirley Analyser Mk2", and tested for fiber maturity and linear density. Fiber maturity ratio was determined using the CSIRO SiroMat maturity tester (Gordon and Phair, 2005; Long et al., 2009). Linear density [μg m^{-1} or millitex (mtex)] which is often referred to as fiber fineness was measured using the CSIRO Cottonscan (Naylor and Purmalis, 2005). Reported measurements of fiber maturity ratio and linear density are means of three and five subsamples, respectively. These instruments were chosen as they are able to measure fiber quality of small samples (<8 g) (Long et al., 2009). Fiber maturity refers to the degree of development or thickening of a fiber. The thicker the layers of cellulose, the more mature the fiber. Fiber linear density also increases with increasing fiber maturity, but is also dependent on fiber perimeter. Immature fiber has micronaire values <3.8 and maturity ratios values <0.85. Fiber that is too mature and coarse has micronaire values >4.5, and density values >220 μg m^{-1} (Bange et al., 2009).

Data Analysis

Generalized linear modeling (GLM) using Genstat 9 (Lawes Agricultural Trust, IACR, Rothamsted, UK) was used to test for differences in micronaire, maturity ratio, and fiber linear density between boll maturities and harvest aid treatments. In these analyses, the harvest aid treatment and boll maturity were treated as fixed effects, and the random factors were replicate and boll maturity.

For data combined across experiments, regression analyses were used to test relationships of seasonal measurements of micronaire, maturity ratio, and linear density for each boll maturity with micronaire, maturity ratio and linear density measured at harvest. Both linear and quadratic regressions were fit using Sigma Plot 11.0 (Systat Software, Inc.). The relative improvement of the quadratic response over the linear response was tested using *F* tests based on residual means squares (RMS) accounting for differences in the function degrees of freedom (Cousens, 1985). Multiple linear regression analyses using Genstat 9 were also used to test the improvement in predictions of final fiber quality with the addition of percent open bolls as a factor in the regressions. Unless otherwise stated, significant differences were identified using LSD at $P < 0.05$.

RESULTS AND DISCUSSION

Changes in the timing of harvest aid application and differences in conditions across experiments created considerable variability and inconsistency in fiber quality among boll maturities (Tables 1 and 2). In Exp. 1, significant differences in micronaire, maturity ratio, and linear density were found among boll maturities, while differences between harvest aid treatments were only found for maturity ratio and linear density (Table 1). The immature bolls in this experiment had lower values for all quality

attributes compared with mature and open bolls which were not significantly different from each other. While there were differences between harvest aid application times for maturity ratio and linear density, there was no consistent trend for changes in quality with later harvest aid timings. The mean maturity ratio was lowest for the 68.4% open boll treatment, but was not significantly different from the 76.9% open boll treatment. The earliest treatments (29.2 and 41.9% open bolls) had the highest maturity ratios, but were only significantly different from the 68.4 and 76.9% open boll treatments. Linear density the earliest treatment (29.2% open bolls) was significantly lower than two other treatments (56.0 and 76.9% open bolls). There were no significant differences among treatments >29.2% open bolls.

In Exp. 2 and 3, significant interactions between boll maturities and harvest aid timings were detected (Table 2). Unlike in Exp. 1, this resulted in instances where fiber qualities of immature bolls were similar to quality of both mature and open bolls at both the same and at different times of harvest aid application timings. There were also instances where mature and open bolls differed at the same time of harvest aid application which did not occur in Exp. 1. Using micronaire of immature bolls as an example, there were two exceptions where micronaire of the immature bolls were not less than the mature and open bolls. The micronaire of immature bolls in Exp. 2 at 58.2% open bolls was not different from the micronaire of the open bolls at 1.6, 14.2, and 89.5% open bolls. In Exp. 3 the immature bolls at 36.3% open bolls had similar quality to the mature bolls measured at the same time and at >16.4% open bolls.

Many similar instances of this situation were also found for comparisons of micronaire between mature and open bolls, and for maturity ratio and linear density among all boll maturities. Overall in Exp. 2 there were six, five, and seven different groups of treatments with similar means of micronaire, maturity ratio, and linear density, respectively. While in Exp. 3 there were six, five, and eight groups for micronaire, maturity ratio, and linear density respectively (Table 2). These groups of treatments in both experiments indicated no consistent effect of either harvest aid or boll maturity on fiber quality.

Fiber quality of boll maturities at similar harvest aid timings also varied among experiments, and most likely reflected the differences in the seasonal growing conditions by all bolls in each maturity category. Temperature during boll-filling is known to affect micronaire (Hesketh and Low, 1968; Gipson and Ray, 1970; Kelly et al., 2008) and each experiment were exposed to differences in their late season temperatures (February–April). During this period, Exp. 2 had the highest daily average temperature (24.5°C) followed by Exp. 1 (23.5°C), and the coolest was Exp. 3 (21.3°C). Micronaire across harvest aid treatments for all boll maturities was lowest in Exp. 3 and was highest in Exp. 2.

This significant variation and lack of consistent changes in quality with harvest aid timing and boll maturities is conceivable. Samples collected for quality assessment at the time of harvest aid application would first, differ in their number and age, and second, most likely have been exposed to differences in growing conditions during their development. These factors would influence fiber quality. Therefore the use of the boll cutting technique that classifies bolls of similar maturity does not imply that fiber quality will be similar when comparisons of boll maturities are made within a season or between seasons. Nor does it mean that quality between boll maturities will be different. Overall the degree of difference in mean fiber quality (across harvest dates in each experiment) of immature, mature, and open bolls varied, ranging between 1.06 and 1.53 for micronaire, 0.13 to 0.14 for maturity ratio, and 28.2 to 30.7 $\mu g\ m^{-1}$ for fiber linear density.

Table 3. Linear and quadratic models of final fiber quality regressed on fiber quality of different boll maturities. Regressions are fitted to data taken from all experiments combined.

Quality parameter	Boll maturity	*n*	r^2 Linear	r^2 Quadratic
Predicting final micronaire				
Micronaire	immature	18	0.73***	0.76***
Micronaire	mature	17	0.41**	0.41*
Micronaire	open	19	0.33*	0.41*
Linear density	immature	19	0.69***	0.68***
Linear density	mature	20	0.28*	0.35**
Linear density	open	19	ns†	ns
Maturity ratio	immature	19	ns	ns
Maturity ratio	mature	20	ns	ns
Maturity ratio	open	19	ns	ns
Linear density + maturity ratio	immature	19	0.81***	–
Predicting final linear density				
Linear density	immature	19	0.58***	0.63***
Linear density	mature	20	0.22*	ns
Linear density	open	19	0.29*	ns
Predicting final maturity ratio				
Maturity ratio	immature	19	ns	ns
Maturity ratio	mature	20	0.31*	0.37*
Maturity ratio	open	19	ns	ns

* Regression significant at the 0.05 level.

** Regression significant at the 0.01 level.

*** Regression significant at the 0.001 level.

† No significant difference at 0.05 level.

Although fiber quality varied among percentages of open bolls across harvest aid application times within experiments and among experiments for the same boll maturity, when fiber quality of these bolls was combined across experiments significant regressions predicted micronaire measured at harvest (Table 3). There were significant linear relationships for micronaire at final harvest with micronaire ($r^2 = 0.73$) (Fig. 1a) and linear density ($r^2 = 0.69$) of immature bolls. For the mature and open bolls, the responses were still significant but substantially poorer in predicting final micronaire ($r^2 \leq 0.41$). Quadratic responses did not significantly improve predictions of final micronaire, and maturity ratio alone did not predict final micronaire with any boll maturity.

However, when the components of micronaire (linear density and maturity ratio) of the immature bolls were included together in a multiple linear regression, they improved the fit of the response ($r^2 = 0.81$) (Fig. 1b). The addition of the interaction term (linear density × maturity ratio) in the multiple regression did not improve the fit.

Similar to micronaire of the immature bolls, fiber linear density of the immature bolls at the time of harvest aid application was significantly related to fiber linear density (quadratic response $r^2 = 0.63$) (Table 3). For predicting final maturity ratio, only regressions using mature bolls were significant (quadratic response $r^2 = 0.37$) (Table 3).

Using multiple linear regression analysis, the ability to predict final micronaire from micronaire or linear density

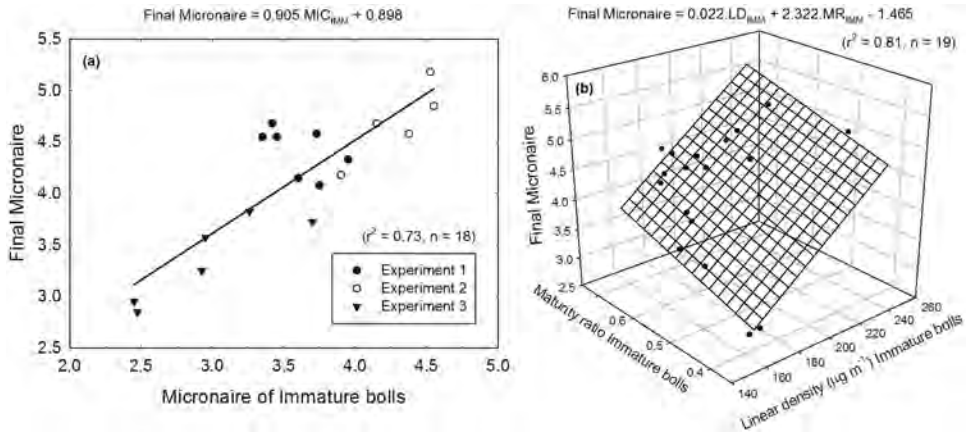

Fig. 1. Cotton micronaire at harvest regressed on (a) micronaire of immature bolls (MIC_{IMM}) and (b) linear density (LD_{IMM}) and maturity ratio (MR_{IMM}) of immature bolls measured at the time of harvest aid application. Regressions are fitted to data taken from all experiments combined.

with maturity ratio of the immature bolls was significantly improved when both the responses included percent open bolls measured at the time of each harvest aid application. The r^2 of the response using micronaire of the immature bolls with percent open bolls was 0.86 (Eq. [1]; Fig. 2), while the r^2 of the response using linear density, maturity ratio and percent immature bolls was 0.88 (Eq. [2]). The addition of interaction terms (micronaire × percent open bolls; linear density × maturity ratio × percent open bolls) in each regression did not improve the predictions. Perhaps the inclusion of percent open bolls improved predictions because it accounted for the proportions of both mature and immature bolls. The proportion of open bolls to total bolls present on a crop is linearly related to percent open bolls ($r^2 = 0.83$; Bange et al., 2010).

$$\text{Final micronaire} = (0.786 \times \text{MIC}_{\text{IMM}}) + (0.009 \times \text{Percent open bolls}) + 0.948 \quad (r^2 = 0.86, p < 0.001) \quad [1]$$

$$\text{Final micronaire} = (0.019 \times \text{LD}_{\text{IMM}}) + (1.767 \times \text{MR}_{\text{IMM}}) + (0.007 \times \text{Percent open bolls}) - 0.930 \quad (r^2 = 0.88, p < 0.001) \quad [2]$$

where final micronaire is the micronaire measured at harvest, MIC_{IMM} is the micronaire of the immature bolls, LD_{IMM} is the linear density (µg m^{-1}) of immature bolls, and MR_{IMM} is the maturity ratio of the immature bolls.

The reason for the quality of the immature bolls better estimating final micronaire over a range of harvest aid application times compared with using the quality of mature and open bolls maybe due to the combined ability of the immature bolls to reflect quality in early and late developing bolls. At early harvest aid applications, immature bolls dominate and reflect final quality. With late harvest applications there are less immature bolls, however these bolls not only contribute to differences in final quality, but also reflect the later growing conditions of bolls that have matured or are close to maturity. The growth of immature bolls late in the season may be indicative of conditions that have persisted during the whole crop boll filling period as their growth will depend on the condition of the crop canopy affecting crop photosynthesis, as well as the overall demand for assimilate that varies with boll load. Competition among bolls for assimilates within the plant has been shown to affect micronaire (Brook et al., 1992; Pettigrew, 1995).

The prediction of final micronaire using multiple linear regressions with the micronaire of the mature or open bolls was significantly improved by including percent open bolls at the time of harvest aid application. However, these predictions were still not as useful as the regression that used the micronaire of immature bolls alone ($r^2 = 0.73$). The r^2 values for the multiple regressions of mature bolls and open bolls with percent open bolls were 0.67 and 0.68, respectively.

Results from this study can be applied in two ways. First, a method to estimate the final fiber micronaire following the impact of application of harvest aids was demonstrated. Second this information could be applied to predict the consequences of later harvest aid applications. Using the final micronaire predicted at the time of initial boll cutting (with an impending harvest aid application), adjustments of the final micronaire

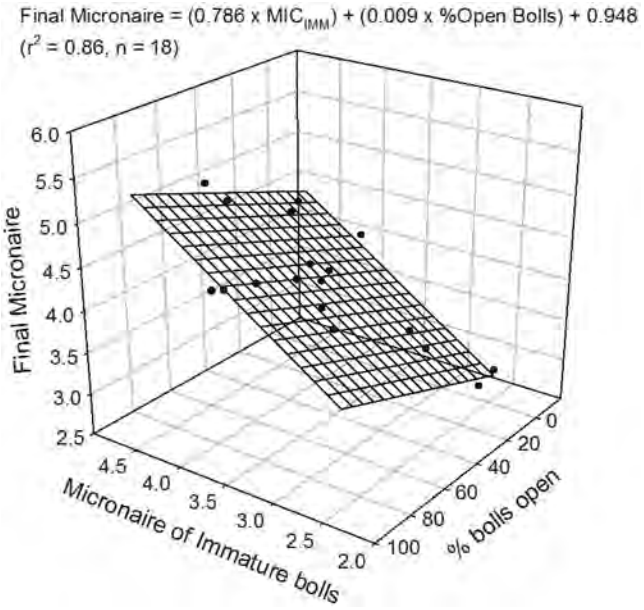

Fig. 2. Response of final micronaire of the crop taken at harvest with micronaire of immature bolls (MIC_{IMM}) and % open bolls at the time of harvest aid application. Regressions are fit to combined data of all three experiments. Regression is Eq. [2] in manuscript.

prediction could be made using functions reported in Bange et al. (2010) that estimate the change in final micronaire with percent open bolls. While the quality of immature bolls in this study provided the greatest precision in predicting micronaire at harvest, there was some precision with the use of the fiber quality of open bolls. The collection of open bolls is much simpler, and the ease of employing this methodology may compensate for some loss of precision in fiber quality prediction. There also may be opportunities to refine this approach by targeting specific times of sampling of open bolls (e.g., 40% open bolls) to improve precision. This refined approach would require testing across more seasons and crops, but warrants further investigation.

End of season fiber sampling methods to estimate micronaire have relied on assumptions of average development of bolls with adjustments made for cooler or warmer seasons. The concept presented here avoids these assumptions; however, it requires further testing in a greater range of environments with crops that have differences in canopy structures and boll loads. Accounting for inherent cultivar differences in micronaire and its components, linear density and maturity ratio would also be required. This concept would also be enhanced by access to reliable, simple, and quick methodologies to measure micronaire or linear density with maturity ratio from small samples collected from the field toward the end of the boll filling period.

Knowledge of final fiber quality and the impact of harvest aid timing may help to improve quality. If estimates of micronaire are low, and climatic conditions are favorable, harvest aid timing could be delayed to allow further boll development and increase micronaire. Conversely, if micronaire is high, harvest aid application may occur earlier and safely avoid issues such as increased neps. The ability to predict the consequences of harvest aid timing on final micronaire suggested that harvest aid applications be applied at 60% open bolls in Exp. 1, applied earlier in Exp. 2, and postponed as long as possible in Exp. 3. This is reported and discussed in more detail in Bange et al. (2010).

CONCLUSIONS

This study identified significant differences and degrees of difference in fiber quality when bolls were defined as mature or immature using the boll cutting technique employed in cotton production to assist with harvest aid decisions. While in each experiment immature bolls had consistently lower micronaire, maturity ratio, and linear density, there were no consistent effects of harvest aid timing on fiber quality for each boll maturity. Despite this variation, there were significant relationships using the fiber quality attributes of immature, mature, and open bolls to reliably predict final quality when harvest aids was applied the same day as sampling. A multiple linear regression using fiber linear density with maturity ratio was best able to predict final fiber micronaire. All regressions were improved when crop status (% open bolls) were also included in multiple linear regressions. The knowledge developed in this study may improve quality at harvest by contributing to the development of simpler, more reliable methodologies for assessing the impact of harvest aid applications.

ACKNOWLEDGMENTS

Thanks also goes to Sarah Jane Caton and Darin Hodgson for assistance in the field, Drs. Greg Constable, Rose Brodrick, and Stuart Gordon for helpful discussions about the results, and Cotton Seed Distributors for provision of planting seed. The Cotton Research and Development Corporation of Australia and the Cotton Catchment Communities Co-operative Research Center both provided partial financial support for this work.

REFERENCES

Bange, M.P., G.A. Constable, S.G. Gordon, G.R.S. Naylor, and M.H.J. Van der Sluijs. 2009. Importance of fibre quality. p. 30–42. *In* M.P Bange et al. (ed.) FIBREpak A guide to improving Australian cotton fibre quality. CSIRO and the Cotton Catchment Communities Coop. Research Centre, Narrabri, NSW, Australia.

Bange, M.P., R.L. Long, G.A. Constable, and S.G. Gordon. 2010. Minimizing immature fiber and neps in upland cotton. Agron. J. 102:781–789.

Bednarz, C.W., D.W. Shurley, and W.S. Anthony. 2002. Losses in yield, quality, and profitability of cotton from improper harvest timing. Agron. J. 94:1004–1011.

Brecke, B.J., J.C. Banks, and J.T. Cothren. 2001. Harvest-aid treatments: Products and application timing. p. 119–143. *In* J.R. Supak and C.E. Snipes (ed.) Cotton harvest management: Use and influence of harvest aids. The Cotton Foundation, Memphis, TN.

Brook, K.D., A.B. Hearn, and C.F. Kelly. 1992. Response of cotton, *Gossypium hirsutum* L., to damage by insect pests in Australia: Manual simulation of damage. J. Econ. Entomol. 85:1368–1377.

Cotton Seed Distributors. 2008. 2008 Variety guide. Wee Waa, New South Wales, Australia.

Cousens, R. 1985. An empirical model relating crop yield to weed and crop density and a statistical comparison with other models. J. Agric. Sci. (Cambridge) 105:513–521.

Faircloth, J.C., K.L. Edmisten, R. Wells, and A.M. Stewart. 2004a. Timing defoliation applications for maximum yields and optimum quality in cotton containing a fruit gap. Crop Sci. 44:158–164.

Faircloth, J.C., K.L. Edmisten, R. Wells, and A.M. Stewart. 2004b. The influence of defoliation timing on yields and quality of two cotton cultivars. Crop Sci. 44:165–172.

Gipson, J.R., and L.L. Ray. 1970. Temperature-variety interrelationships in cotton. 1. Boll and fibre development. Cotton Gr. Rev. 47:257–271.

Gordon, S.G., and N.L. Phair. 2005. An investigation of the interference colours transmitted by mature and immature cotton fiber under polarised light microscopy. p. 2284–2290. *In* Proc. Beltwide Cotton Conf., New Orleans, LA. 4–6 Jan. 2005. Natl. Cotton Council of Am., Memphis, TN.

Hearn, A.B., and G.P. Fitt. 1992. Cotton cropping systems. p. 85–142. *In* C.J. Pearson (ed.) Ecosystems of the world-Field crop ecosystems. Elsevier, London.

Hesketh, J.D., and A. Low. 1968. Effect of temperature on components of yield and fibre quality of cotton varieties of diverse origin. Cotton Gr. Rev. 45:243–257.

Kelly, D., M.P. Bange, and G.A. Constable. 2008. Unraveling the micronaire challenge. The Australian Cottongrower 29:24–26.

Kerby, T.A., J. Supak, J.C. Banks, and C.E. Snipes. 1992. Timing defoliation using nodes above cracked boll. p. 155–157. *In* Proc. Beltwide Cotton Conf., Nashville, TN. 6–10 Jan. 1992. Natl. Cotton Council of Am., Memphis, TN.

Leffler, H.R. 1987. Mineral compartmentation within the boll. p. 301–309. *In* J.R. Mauney and J.M. Stewart (ed.) Cotton physiology: Number one. The Cotton Foundation, Memphis, TN.

Long, R., M. Bange, S. Gordon, and G. Constable. 2009. Measuring the maturity ratio of developing cotton fibers using an automated polarised light microscopy technique. Text. Res. J. 80:463–471.

Naylor, G.R.S., and M. Purmalis. 2005. Update on Cottonscan: An instrument for rapid and direct measurement of fibre maturity and fineness. p. 2302–2306. *In* Proc. Beltwide Cotton Conf., New Orleans, LA. 4–7 Jan. 2005. Natl. Cotton Council of Am., Memphis, TN.

Pettigrew, W.T. 1995. Source-to-sink manipulation effects on cotton fiber quality. Agron. J. 87:947–952.

Reid, P.E. 2003. Sicot 71. Plant Varieties J. 16:35–36.

Rochester, I.J. 2007. Nutrient uptake and export from an Australian cotton field. Nutr. Cycling Agroecosyst. 77:213–223.

Snipes, C.E., and C.C. Baskin. 1994. Influence of early defoliation on cotton yield, seed quality, and fiber properties. Field Crops Res. 37:137–143.

Stewart, J.M. 1987. Integrated events in the flower and fruit. p. 261–300. *In* J.R. Mauney and J.M. Stewart (ed.) Cotton physiology: Number one. The Cotton Foundation, Memphis, TN.

Thibodeaux, D.P., O. Hinojosa, and W.R. Meredith. 1993. Application of AFIS measurement technology to evaluating the quality of cotton treated with Prep™. p. 1113–1115. *In* Proc. Beltwide Cotton Conf., New Orleans, LA. 10–14 Jan. 1993. Natl. Cotton Council of Am., Memphis, TN.

Minimizing Immature Fiber and Neps in Upland Cotton

Michael P. Bange,* Robert L. Long, Greg A. Constable, and Stuart G. Gordon

ABSTRACT

Immature cotton (*Gossypium hirsutum* L.) fibers and neps in ginned cotton will affect textile quality and thus can affect overall industry reputations. This study conducted three field studies that systematically varied the timing of harvest aid application to generate differences in the amount of immature fiber and levels of neps in crops at harvest. The aim was to ascertain what crop conditions (percent open bolls, number of immature bolls, percent immature bolls, and percent immature lint mass) at the time of application contribute to these differences, and assess whether these outcomes are influenced by 0, 1, 2 lint cleaning passes. Earlier harvest aid treatments increased neps and the level of neps was best related to fiber linear density ($r^2 = 0.78$). All measurements of crop condition at harvest aid application explained changes in yield and fiber properties well, although the percent immature bolls ($r^2 > 0.67$) can be applied when crops are nonuniform in their maturity, and when they contain fruiting gaps. Relationships between lint cleaning passes and crop condition at harvest aid application showed an interaction between earlier harvest treatments and lint cleaning passes. One lint cleaning pass contributed between 95 and 141 count g^{-1} more neps, while a second pass added between 101 and 181 count g^{-1} more neps. This information will be valuable in refining strategies that aim to optimize both yield and fiber quality (including less neps). This study also supported the current recommendation of applying harvest aids at 60% open bolls.

Immature bolls will usually contain immature cotton fibers, which are prone to entanglement and the formation of neps (Anthony et al., 1988; Gordon, 2007). Neps are small entanglements of cotton fibers that are created during mechanical processing and often contain dead or immature fibers (Hebert et al., 1988). Immature fiber and neps even in small amounts are undesirable (Ethridge and Simonton, 2004) as they decrease mill processing efficiency and ruin the appearance of finished yarns and fabrics. Immature fibers and neps absorb less dye and reflect light differently, and consequently appear as under-dyed barred patterns and/or "flecks" on finished fabrics (Bradow et al., 1996; Goynes et al., 1997; Mangialardi et al., 1987). Rarely are there direct penalties for growers when there is high incidence of neps, their presence can however, affect overall the sources reputation when cotton arrives at spinning mills (Gordon et al., 2004).

Cotton crops actively growing at the end of a season that experience an abrupt end caused by cold temperatures may increase the number of immature bolls. Also, premature application of chemical harvest aids that force bolls to open and defoliate leaves aimed at preserving quality by avoiding possible weathering, or reducing micronaire will increase immature bolls at harvest. Both situations may lead to less mature fibers (Bednarz et al., 2002) and increased neps once cotton is harvested and ginned (Thibodeaux et al., 1993).

Many studies have also shown reductions in micronaire (an indirect measurement of both fiber linear density [fineness] and maturity) with premature applications of harvest aids and have related this to crop condition at the time of harvest aid application such as percent open bolls and nodes above cracked boll (NACB) (Bednarz et al., 2002; Faircloth et al., 2004a, 2004b; Kerby et al., 1992; Snipes and Baskin, 1994; Thibodeaux et al., 1993). There have been however, no studies that have attempted to relate crop condition at the time of harvest aid application to the direct level of immature fiber in the crop and the consequences of this immaturity on differences in neps.

This study uses the timing of harvest aid application to vary the amount of immature fiber and levels of neps in the crop to: (i) ascertain the crop conditions that contribute to differences in nep levels; (ii) assess whether these outcomes are influenced by changes in the number of lint cleaning passes. In revealing these relationships it is anticipated that this information will be valuable in refining crop monitoring and harvest preparation strategies that aim to optimize both lint yield and fiber quality (including the reduction in neps).

MATERIALS AND METHODS

Cultural Details and Treatments

Three harvest aid timing field experiments were conducted at the Australian Cotton Research Institute (ACRI) at Narrabri (30° S, 150° E). This is a semiarid environment with a uniform gray cracking clay (USDA Soil Taxonomy: Typic Haplustert)

M.P. Bange, CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW 2390, Australia, and Cotton Catchment Communities Co-operative Research Centre, Narrabri, NSW 2390, Australia; G.A Constable, CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW 2390, Australia; R.L. Long and S.G. Gordon, CSIRO Materials Science and Engineering, P.O. Box 21, Belmont, VIC, 3216, Australia and Cotton Catchment Communities Co-operative Research Centre, Narrabri, NSW 2390, Australia. Received 3 Nov. 2009. *Corresponding author (Michael.Bange@csiro.au).

Published in Agron. J. 102:781–789 (2010)
Published online 10 Feb. 2010
doi:10.2134/agronj2009.0454

Abbreviations: NACB, nodes above cracked boll.

Table 1. Crop condition at the time of each harvest aid application and impact on lint yield for each for all experiments.

Harvest aid treatment	DAS†	Open bolls	No. immature bolls	Immature bolls	Immature lint mass	NACB	Lint yield
		%	m^{-2}	%			
			Experiment 1				
1	143	29.2	104.7	67.5	60.8	9.1	2424
2	147	41.9	73.9	41.0	37.1	6.9	2444
3	152	56.0	46.8	23.4	20.1	6.1	2620
4	157	68.4	41.0	22.2	16.8	4.5	2745
5	161	76.9	35.6	21.1	16.5	3.7	2814
6	166	85.9	32.3	12.5	9.0	3.1	2739
7	171	93.0	11.8	6.1	4.5	2.9	2632
Control	–	100.0					2781
LSD (0.05)	–	3.89***	37.3***	15.85***	13.99***	1.5***	213**
			Experiment 2				
1	136	1.6	85.6	64.9	57.2	7.9	2228
2	140	14.2	73.2	56.6	48.9	7.1	2576
3	145	29.9	77.4	50.1	39.8	5.7	2623
4	150	45.6	58.1	36.1	29.0	4.6	2844
5	154	58.2	22.0	19.8	12.8	4.1	2711
6	159	73.8	11.2	10.2	7.4	2.7	2692
7	164	89.5	12.0	10.1	5.3	2.0	2828
Control	–	100.0					2803
LSD (0.05)	–	4.31***	15.2***	9.2***	9.29***	1.0***	271**
			Experiment 3				
1	143	0.6	151.6	88.2	72.7	10.2	1732
2	155	9.0	122.4	81.0	70.3	8.0	1893
3	162	16.4	93.2	72.4	65.2	7.3	2292
4	169	25.5	105.9	72.2	62.0	6.3	2371
5	176	36.3	62.1	40.4	27.8	4.4	2758
Control	185	53.5	28.0	20.0	15.2	2.1	2580
LSD (0.05)	–	6.78***	50.47**	16.9***	17.86***	2.0***	493**

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

† DAS = days after sowing when treatment applied; NACB = nodes above cracked boll.

in northwestern New South Wales, Australia. Experiments 1 and 2 consisted of seven harvest aid application dates with a control which allowed all bolls to fully mature, while Exp. 3 had five applications and a control that was treated 185 days after sowing (DAS) (Table 1). All experiments used a randomized complete block design with four replications.

Treatment plots (8 by 10 m), contained eight rows spaced at 1 m. In the center two rows of each plot harvest aid, a mixture of leaf defoliant and a boll opener was applied at approximately 5 d intervals in Exp. 1 and 2, and 7 d intervals in Exp. 3 from low to high percent open bolls. Initiation of harvest aid treatments in Exp. 1 was targeted around 20% open bolls, while in Exp. 2 and 3 an attempt was made to generate treatments with increased immature fiber so the first harvest aid treatment was following the appearance of first open boll. Harvest aids were sprayed with a calibrated CO_2 pressurized boom with total swath width 3.0 m using flat fan nozzles (110–01) at 200 kPa delivering 100 L ha^{-1} of spray solution. The chemical and rates were: 0.2 L ha^{-1} Dropp Liquid (Bayer CropScience, active constituent 500 g L^{-1} Thidiazuron); 3 L ha^{-1} Prep 720 (Bayer CropScience, active constituent 720 g L^{-1} Ethephon); and 2 L ha^{-1} D-C Tron (Caltex, active constituent 991ml L^{-1} Petroleum Oil).

Experiments were sown with a commercial row crop planter (Exp. 1–15 Oct. 2005; Exp. 2–20 Oct. 2006; Exp. 3–16 Oct. 2007) using upland cotton. In Exp. 1 and 2 Bollgard II Roundup Ready (Monsanto Co., St. Louis, MO) cultivar Sicot 71BR (CSIRO, Australia) was used while Exp. 3 used non-transgenic Sicot 71 (CSIRO, Narrabri, Australia; Reid, 2003), the recurrent parent of Sicot 71BR. Both cultivars have normal leaf shape, medium to late maturity and compact growth habit. Typical fiber quality attributes of Sicot 71BR are 29.2 mm fiber length, 31 cN tex^{-1} fiber strength, and micronaire of 4.5. Attributes of Sicot 71 are similar fiber length and fiber strength to Sicot 71BR, and micronaire of 4.4 (Cotton Seed Distributors, 2008). All experiments were established and grown with full irrigation using nonlimiting N and thorough insect control as described in Hearn and Fitt (1992). Nitrogen was applied as anhydrous ammonia (injected below and to the side of the plant line) 4 wk before sowing at a rate of 200 kg N ha^{-1}. The rate of N was determined on the basis of a N replacement program that accounts for N use in previous cotton crops (Rochester, 2007). Meteorological data for the experimental period were measured 2 km from the field site.

Measurements of Crop Condition

To establish crop condition when harvest aid treatments were applied, a number of measurements were taken on the control plots on each day of treatment application. In a fixed area of 1 m^{-2} in each control plot, a count of open bolls

(defined as when two sutures on the boll had split) was taken to determine the percentage of open bolls. The lint collected from these samples was kept and combined to calculate yield components (final boll number and seed cotton per boll). On each day of treatment 0.5 m^{-2} of plants were harvested to determine the following: on all plants NACB recorded as the total number of main-stem nodes between the uppermost harvestable boll and the highest first position cracked boll (Kerby et al., 1992); on five plants the number of mature and immature bolls were counted to determine number of immature bolls (bolls m^{-2}) and percentage immature bolls [immature bolls/(mature bolls + open bolls) × 100]. Lint collected from both mature and immature bolls was kept to calculate the relative mass of immature cotton to the total mass of cotton [% immature lint mass = immature lint mass/(open boll lint mass + lint mass) × 100]. Immature bolls were determined by cutting bolls perpendicular to their vertical axis and assessing the color of the seed coats contained within the bolls. A seed coat that was not dark was deemed immature (Brecke et al., 2001).

To determine lint yield the fourth row of each plot was harvested with a spindle picker and the seed cotton weighed. Seed cotton from each plot was ginned to determine gin turnout (percent lint), which was used to calculate lint yield. Samples were ginned using a 20 saw gin with a precleaner located at the ACRI (Continental Eagle, Prattville, AL).

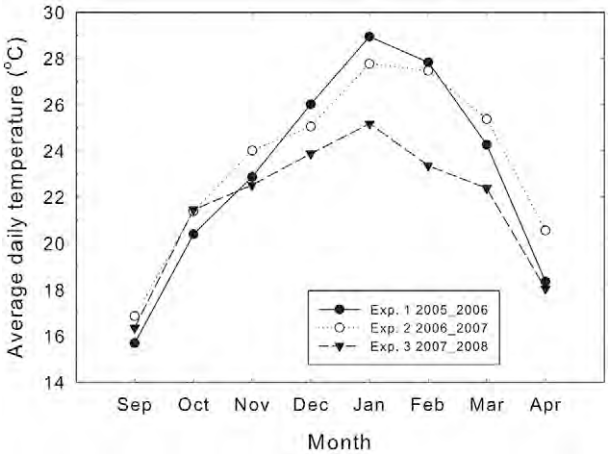

Fig. 1. Monthly average daily temperature for the three field experiments.

Lint was then subsampled and subjected to one of three lint cleaning treatments (0, 1, and 2 lint cleaning passes). Lint cleaning treatments were conducted using a purpose built experimental lint cleaner with a 25.4 cm saw and four grid bars. The lint cleaner saw was operated at a speed of 855 rpm

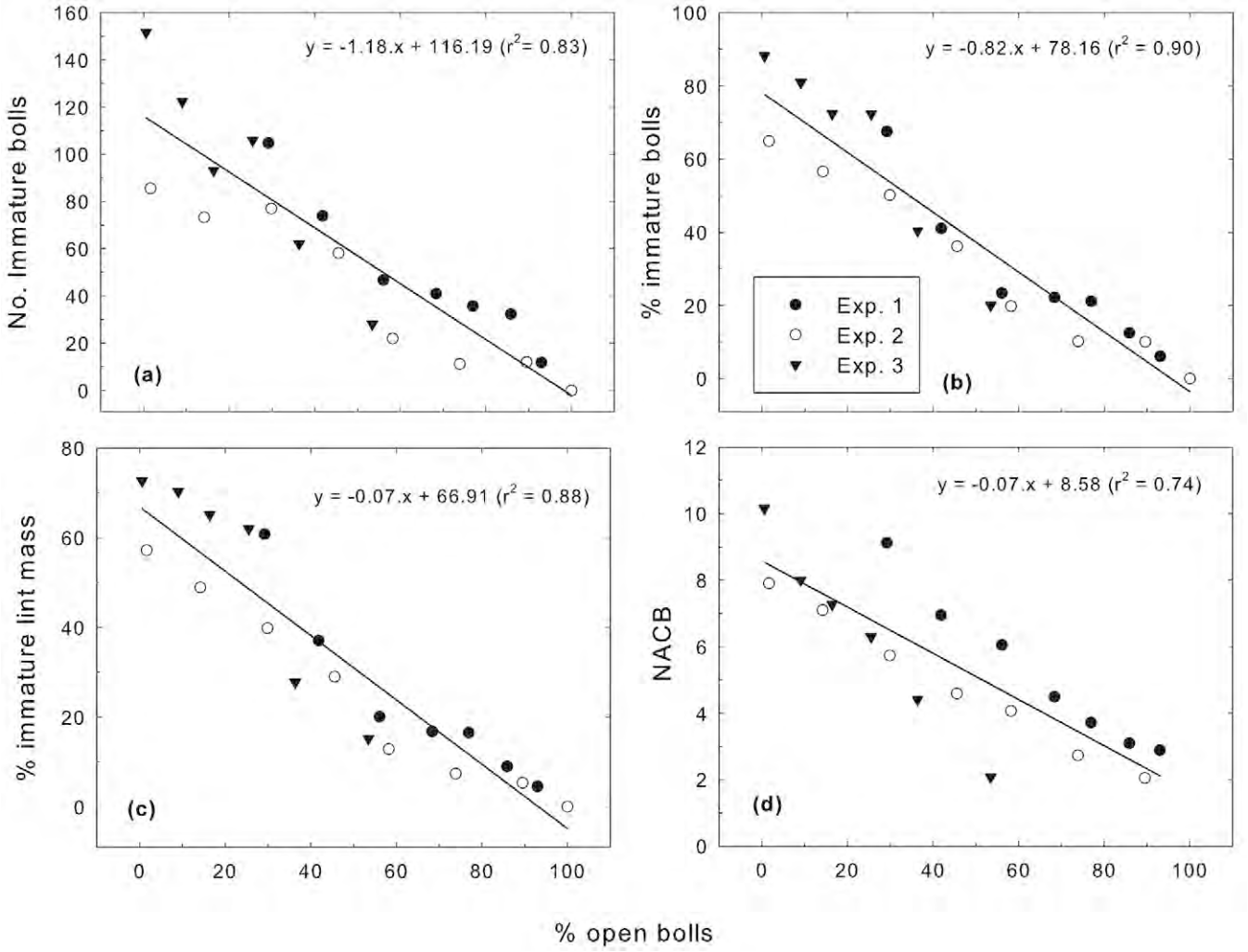

Fig. 2. Relationships used to estimate the (a) number of immature bolls, (b) percent immature bolls, (c) percent immature lint mass, and (d) nodes above cracked boll (NACB) when crops were at 60% open bolls.

with a combing ratio of 23 to the feed zone. Cotton was fed into the lint cleaner with a relatively light loading ratio of 100 g m^{-2}. Samples were taken from these treatments for fiber quality analysis.

Fiber Quality Analyses

Lint samples were subjected to quality assessment using the Spinlab High Volume Instrument (HVI) model Classing 900 (Zellweger Uster, Knoxville, TN). Fiber characteristics measured on the HVI were upper half mean length (mm), strength (cN tex^{-1}), and micronaire. Recovered HVI material was then blended through one passage of a SDL "Shirley Analyser Mk2", and then tested for fiber maturity, measured as the maturity ratio using the CSIRO SiroMat maturity tester (Gordon and Phair, 2005; Long et al., 2009), and linear density [millitex (mtex)] which is often referred to as fiber fineness using the CSIRO Cottonscan (Naylor and Purmalis, 2005). Reported measurements of fiber maturity ratio and linear density are an average of three and five subsamples, respectively.

For neps analysis, ginned lint samples (from 0, 1, and 2 lint cleaning passes) were assessed by the Advanced Fiber Information System (AFIS PRO) (Uster Technologies, Switzerland).

Table 2. Regression coefficients for responses that related crop condition to lint yield, micronaire, neps, fiber maturity ratio and linear density. The change in variable is calculated as the change from the control harvest aid treatment for each experiment. Regressions used are a two parameter exponential function ($y = a \times e^{bx}$). Examples of fitted functions are shown in Fig. 3. All regressions were highly significant ($P < 0.001$).

Variable/crop condition	r^2	a	b
Lint yield change, kg ha^{-1}			
Percent open bolls	0.75	–773.87	–0.049
No. immature bolls	0.71	–40.64	0.021
Percent immature bolls	0.75	–17.51	0.044
Percent immature lint mass	0.75	–14.95	0.054
NACB	0.74	–18.64	0.378
Micronaire change			
Percent open bolls	0.77	–0.951	–0.042
No. immature bolls	0.66	–0.064	0.019
Percent immature bolls	0.76	–0.034	0.039
Percent immature lint mass	0.79	–0.028	0.048
NACB	0.65	–0.030	0.349
Nep count change (count g^{-1})†			
Percent open bolls	0.80	252.05	–0.054
No. immature bolls	0.70	10.30	0.022
Percent immature bolls	0.76	3.90	0.048
Percent immature lint mass	0.76	2.50	0.063
NACB	0.73	4.28	0.411
Maturity ratio change			
Percent open bolls	0.57	–0.1613	–0.05660
No. immature bolls	0.65	–0.003932	0.02662
Percent immature bolls	0.68	–0.001265	0.05748
Percent immature lint mass	0.67	–0.0009664	0.7136
NACB	0.61	–0.0010	0.5277
Linear density change (mtex)			
Percent open bolls	0.70	–33.54	–0.041
No. immature bolls	0.69	–2.15	0.020
Percent immature bolls	0.79	–1.02	0.041
Percent immature lint mass	0.82	–0.72	3.317
NACB	0.57	–0.30	0.054

† Sample subjected to one cleaning pass.

Reported AFIS PRO neps [including fiber and seed coat neps (count g^{-1})] measurements are an average of five subsamples.

Data Analysis

All ANOVA and multiple linear regression analysis were conducted using the Genstat 9 statistical package (Lawes Agricultural Trust, IACR, Rothamsted, UK). The relationship between fiber quality properties and between lint yield and its components was assessed by correlation analysis. To account for seasonal effects and for cultivar differences the change in lint yield, micronaire, maturity ratio, linear density, and nep count was calculated as the difference between each harvest aid treatment and the control for each experiment which was then related to each crop condition measurement using a two parameter exponential relationship. Regression analyses were conducted using Sigma Plot 9.0 (Systat Software, Inc., San Jose, CA).

RESULTS AND DISCUSSION

Crop Condition at the Time of Treatment

In all experiments earlier harvest aid treatment applications had significantly less percent open bolls but increased number of immature bolls, percent immature bolls, percent immature lint mass, and NACB (Table 1). While crops in Exp. 1 and 2 had adequate time to fully mature (100% open bolls), Exp. 3 experienced cooler weather (Fig. 1) and the crop was delayed, resulting in the last harvest aid treatment being the control treatment with only 53% open bolls. Consequently Exp. 3 had higher numbers of immature bolls (resulting in more immature lint), especially in the earlier harvest aid treatments.

When crop condition data from all experiments was combined there were significant linear relationships between percent open bolls and all other measures of crop condition at the time of harvest aid application (Fig. 2). These relationships were used to calculate crop condition using other measures. The current recommendation for application of harvest aids is 60% open bolls (Snipes and Baskin, 1994). In this study at 60% open bolls the number of immature bolls were 45 boll m^{-2}, percent immature bolls was 29%, percent immature lint mass was 24%, and NACB = 4.4. Bednarz et al. (2002) also showed a significant relationship between percent open bolls and NACB, and at 60% open bolls NACB = 4. The percent open bolls measure is not directly analogous to percent immature bolls as the boll cutting technique identifies bolls that are mature but not open (approximately 11% bolls at 60% open bolls).

Lint Yield and Yield Components

In all experiments lint yield was significantly affected by harvest aid treatment (Table 1) with the greatest yield reduction occurring in Exp. 2 and 3 with the earlier treatments. Less lint yield was attributed to smaller boll sizes (seed cotton per boll) in all experiments and lower gin turnout in Exp. 2 and 3 (data not presented). Across all experiments lint yield was positively correlated with boll size ($r = 0.55$, $P < 0.001$) and gin turnout ($r = 0.70$, $P < 0.001$). These differences would have occurred as a result of reductions in both seed and fiber growth (Leffler, 1987) caused by substrate limitations from leaf loss and premature opening of bolls. Snipes and Baskin (1994) also

found that boll size was reduced as a result of earlier harvest aid treatments.

Change in lint yield was best represented with relationships to percent open bolls, percent immature bolls, and percent immature lint mass (all with $r^2 = 0.75$) (Table 2, Fig. 3). The relationships to NACB and number of immature bolls were significant but did not represent the data as well ($r^2 = 0.74$ and 0.71, respectively). Similar to results of others (Bednarz et al., 2002; Snipes and Baskin, 1994; Siebert and Stewart, 2006) yield was substantially reduced when harvest aids were applied before 60% open boll. Lint yield was reduced by 68 kg ha^{-1} when harvest aid treatments were applied at 40% open bolls from 60% open bolls. Measured lint yield reductions resulting from harvest aid applied at 60% compared with 40% open bolls have varied {Bednarz et al., 2002 [52–166 kg ha^{-1}; Faircloth et al., 2004 (0–77 kg ha^{-1}); Snipes and Baskin, 1994 (30–90 kg ha^{-1})] }.

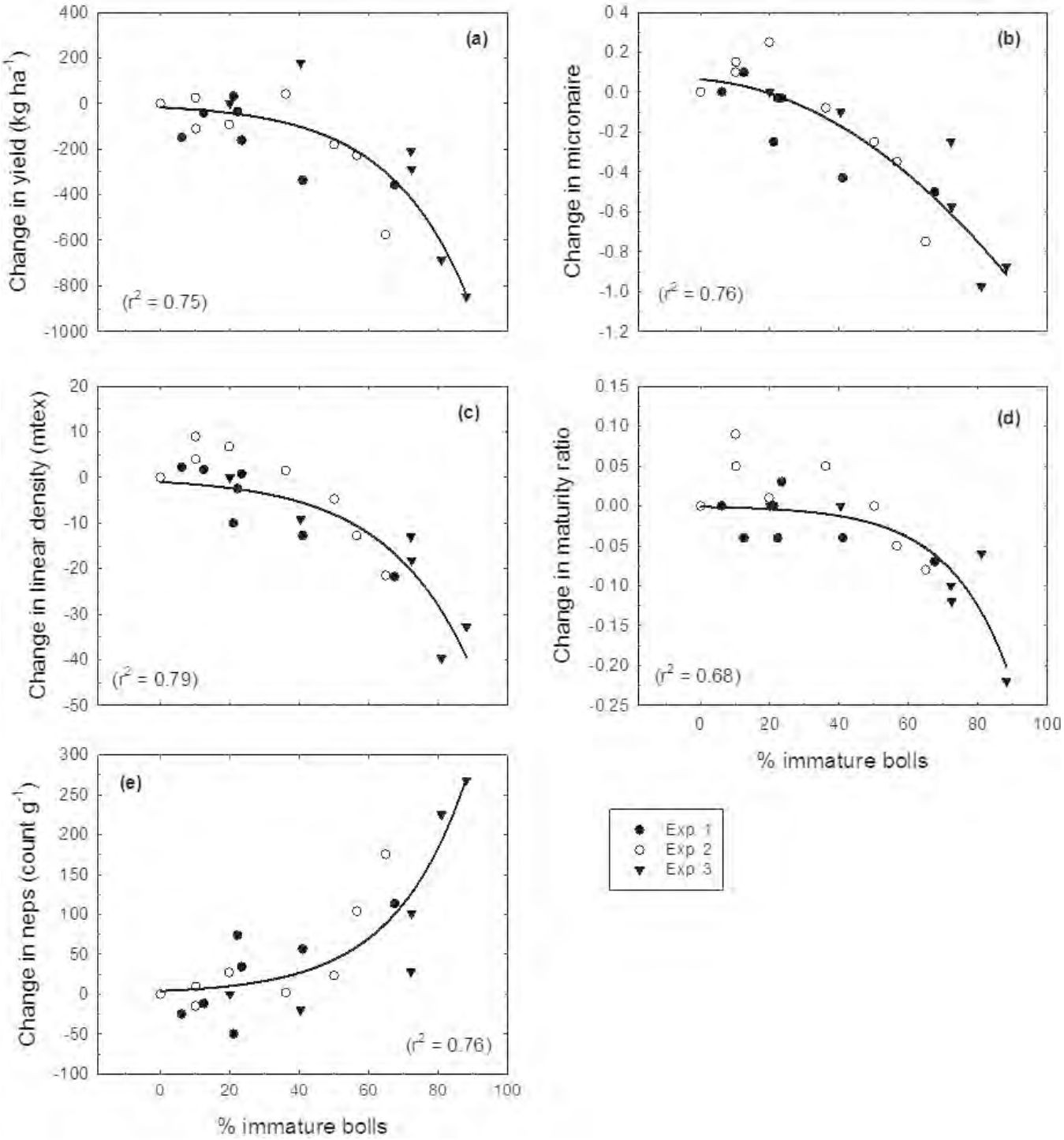

Fig. 3. An example of response of changes in (a) lint yield, (b) micronaire, (c) linear density,(d) maturity ratio, and (e) neps with crop condition (percent immature bolls) at harvest aid treatment across all experiments. The change in variable is calculated as the change from the control harvest aid treatment for each experiment. Regressions use a two parameter exponential function ($y = a \times e^{bx}$). Nep change is for one lint cleaning pass.

Table 3. Impact of harvest aid timing on fiber upper half mean length (UHML), bundle strength, micronaire, fiber maturity ratio, and linear density for all experiments.

Harvest aid treatment	Length UHML	Bundle strength	Micronaire	Maturity ratio	Linear density
	mm	cN tex^{-1}			mtex
		Experiment 1			
1	28.96	31.05	4.08	0.88	171.50
2	29.72	31.37	4.15	0.91	180.50
3	29.21	30.30	4.55	0.98	194.00
4	28.96	29.62	4.55	0.91	190.75
5	30.23	31.70	4.33	0.95	183.25
6	29.97	30.77	4.68	0.91	195.00
7	29.72	30.65	4.58	0.95	195.50
Control	29.97	31.37	4.58	0.95	193.25
LSD (0.05)	0.76*	1.75	0.36*	0.10	12.22**
		Experiment 2			
1	29.46	31.88	4.18	0.82	179.00
2	29.46	30.48	4.58	0.85	187.75
3	29.72	30.93	4.68	0.90	195.75
4	29.46	30.95	4.85	0.95	202.00
5	28.45	28.85	5.18	0.91	207.25
6	29.21	30.38	5.08	0.95	204.50
7	29.72	31.40	5.03	0.99	209.50
Control	29.97	31.35	4.93	0.90	200.50
LSD (0.05)	1.02*	2.12	0.36***	0.10*	10.72***
		Experiment 3			
1	29.27	32.00	2.95	0.53	158.50
2	29.91	32.25	2.85	0.69	151.50
3	30.35	31.88	3.25	0.63	173.00
4	30.10	31.65	3.58	0.65	178.20
5	30.29	31.00	3.73	0.75	182.00
Control	30.42	30.98	3.83	0.75	191.20
LSD (0.05)	0.54**	1.41	0.26***	0.15*	9.26**

* Significant at the 0.05 level.

** Significant at the 0.01 level.

*** Significant at the 0.001 level.

Fiber Quality

In all experiments earlier harvest aid treatments significantly lowered fiber length, micronaire and fiber maturity (Table 3) while the levels of fiber neps were increased (Table 4). Fiber strength was unaffected. Discounts for Australian growers can be applied when fiber length and strength is <26.2 mm and 27 cN tex^{-1}, respectively. For cotton spinning purposes fiber length across all treatments and experiments was acceptable (>28.6 mm), as was fiber strength (>29 cN tex^{-1}). For micronaire the late harvest aid application treatments of Exp. 2 was high (>5.0) and was low (<3.8) in all treatments of Exp. 3. These values would have attracted significant price discounts for growers, although earlier applications of harvest aids in Exp. 2 would have prevented price discounts.

The level of neps from cotton with no lint cleaning in some of the early harvest aid treatments either exceeded or was close to unacceptable levels (<250 neps g^{-1}) (Gordon et al., 2004). Cotton that had been processed by lint cleaners following ginning had very few instances where levels did not exceed 250 count g^{-1}. Only treatments in Exp. 1 and 2 with late applications of harvest aid following 1 lint cleaning pass had levels similar or lower than 250 count g^{-1}. If high levels of neps are detected, spinners incur losses during processing and the final yarn appearance is reduced.

More neps (in cotton with no lint cleaning) and immature cotton was associated with earlier harvest aid treatments across all experiments (Table 4). The number of neps was negatively correlated with linear density ($r = -0.83$), maturity ratio ($r = -0.63$), and micronaire ($r = -0.74$) indicating that production of immature or low linear density fiber was most likely the reason for increased neps (Anthony et al., 1988; Dever and Gannaway, 1988; Hebert et al., 1988; Mangialardi et al., 1987). Upland cotton fiber with maturity ratios < 0.85 or a micronaire-value <3.5 are generally considered immature.

Regression analyses showed that a quadratic was best able to describe neps (with no lint cleaning) from fiber linear density ($r^2 = 0.78$; Fig. 4). The addition of fiber maturity ratio and the interaction of fiber maturity ratio and linear density however, did not improve the fit. This was not unexpected given the strong association between maturity ratio and linear density ($r = 0.76$). Micronaire also did not predict the levels of neps ($r^2 = 0.63$) as well as linear density. Van der Sluijs and Hunter (1999) were able to predict neps with micronaire and length uniformity. In this study it was not unexpected that uniformity did not predict neps as there was no variability in fiber length and uniformity. It is also recognized that the two earliest treatments in Exp. 3 had strong leverage on these regression outcomes, and thus more data collected when lint has linear densities <170 mtex will help to substantiate the shape of response of neps to linear density,

Others have shown that earlier applications of harvest aids leading to crop termination have also reduced micronaire (Kerby et al., 1992; Siebert and Stewart, 2006; Snipes and Baskin, 1994). Thibodeaux et al. (1993) with an early application of a boll opener on late season bolls reduced both micronaire and fiber maturity resulting in more neps.

Across seasons and with treatments, the increase in neps was reflected by similar reductions in micronaire, fiber maturity ratio, and fiber linear density (Table 2, Fig. 3). The change in micronaire was best represented by the relationship to percent immature lint mass ($r^2 = 0.79$), while NACB was the poorest ($r^2 = 0.65$). Fiber maturity changes were best represented by percent immature bolls ($r^2 = 0.68$), and the poorest with percent open bolls ($r^2 = 0.57$). For neps percent open bolls was the best measure ($r^2 = 0.80$) followed by percent immature bolls and percent immature lint mass (both $r^2 = 0.76$). Fiber linear density was best represented by percent immature lint mass ($r^2 = 0.82$) followed by percent immature bolls ($r^2 = 0.79$). No significant relationship for changes in fiber length was determined.

Like yield, fiber attributes were only substantially affected once harvest aid treatments were applied before 60% open bolls. The level of neps in fiber with no lint cleaning was increased by 29 counts g^{-1}, associated with 0.10 reduction in micronaire, 0.01 reduction in maturity ratio, and 3.64 mtex reduction when harvest aids were applied at 40% open bolls from 60% open bolls. Application of harvest aids after 60%

Table 4. Effect of harvest aid treatment and 0, 1, and 2 lint cleaning passes on the level of neps for each experiment.

Harvest aid treatment	0 lint cleaners	1 lint cleaner pass	2 lint cleaner passes
		count g^{-1}	
Experiment 1			
1	247.8	399.5	521.8
2	243.3	342.8	456.8
3	262.8	320.2	427.5
4	206.0	359.8	455.0
5	178.8	236.0	350.0
6	194.5	274.5	354.3
7	217.8	261.3	358.8
Control	153.8	286.0	363.3
Mean neps (lint cleaner)	213.1	310.0	410.9
LSD harvest aid treatment			63.0***
LSD lint cleaner			38.6***
LSD harvest aid treatment × lint cleaner			109.2
Experiment 2			
1	263.0	428.8	568.5
2	233.8	347.0	441.8
3	195.3	276.8	415.0
4	171.3	255.3	362.2
5	199.5	290.8	381.8
6	162.5	262.8	408.0
7	180.8	238.5	346.2
Control	183.5	253.2	342.2
Mean neps (lint cleaner)	198.7	294.1	408.2
LSD harvest aid treatment			46.0***
LSD lint cleaner			28.2***
LSD harvest aid treatment × lint cleaner			79.7
Experiment 3			
1	340.2	573.0	810.8
2	364.3	529.8	774.0
3	249.0	406.0	561.2
4	220.7	332.5	493.0
5	192.0	284.7	436.2
Control	197.5	304.7	442.7
Mean (lint cleaner)	260.6	405.1	586.3
LSD harvest aid treatment			40.2***
LSD lint cleaner			28.4***
LSD harvest aid treatment × lint cleaner			69.6***

*** Significant at the 0.001 level.

open bolls did not affect microniare as was found by Faircloth et al. (2004a).

Similar to other studies the number of lint cleaning passes had significant effects on nep levels (Anthony et al., 1988; Dever and Gannaway, 1988; Hebert et al., 1986; Mangialardi, 1985) (Table 4). One lint cleaning pass contributed an extra 97 and 95 neps for Exp. 1 and 2, respectively. A second lint cleaning pass contributed 101 and 114 for Exp. 1 and 2, respectively in addition to neps generated by 1 lint cleaning pass. In Exp. 3 there was a significant interaction between the timing of harvest aid treatment and the number of lint cleaning passes where the earliest two harvest aid treatments had substantially more neps with addition of lint cleaning. As a result, the mean contribution of lint cleaning to neps were 144 more neps for 1 lint cleaning pass and another 181 more neps for a second pass. Anthony et al. (1988) and Mangialardi (1985) also showed that the increase in neps for each lint cleaning pass was essentially equal in magnitude except when lint had been excessively weathered.

To account for the effect of lint cleaners on the level of neps across seasons and treatment differences associated with Exp. 3 the change in nep count of each harvest aid treatment and lint cleaning passes from the control treatment with 0 lint cleaning was related to percent open bolls, percent immature bolls, and percent immature lint mass (Table 5, Fig. 5). A three parameter exponential function was chosen as it accounted for the steeper increase in neps with later harvest aid treatments and more lint cleaning passes. The best responses were those that related change in neps with percent immature lint mass, followed by percent immature bolls then percent open bolls. These responses highlighted a consistent increase in neps with more immature bolls/cotton, and the relative stability in the extra contribution of lint cleaners until around 20% immature bolls (62% mature bolls; 52% immature lint) where the effect of the interaction of larger amounts of immature cotton (caused by early harvest aid treatments) and lint cleaning had taken effect.

On the basis of yield, micronaire, fiber maturity, and neps the results here also support the current recommendation of applying harvest aids at 60% open bolls or around 4 NACB in uniformly maturing cotton crops. This study however, showed across three different seasons that all these attributes were consistently affected before 60% open bolls. The decision on whether to apply harvest aids earlier than 60% open bolls is often affected by yield and quality losses from crop weathering and/or the overall maturity of the crop. If seasons have been cooler and crops are delayed (as was the case with Exp. 3 in this study) fibers will already be less mature and the risk of harvesting immature fiber and creating neps is already inherently greater. Therefore applying harvest aids before 60% open bolls only increases the chances of lowering micronaire, harvesting more immature fiber and generating more neps, attracting discounts to growers and affecting quality of textiles produced from this cotton. This is especially made more important when lint cleaning is applied in the gin (Fig. 4). Ensuring that cotton is as mature as possible when delivered to the gin will help to contain these issues. Applying harvest aids earlier in this study did reduce micronaire when it was high (as was the case in Exp. 2), but it also reduced yield negating any potential benefit to the grower. The ability to predict whole of seasonal effects on micronaire/maturity at the time of harvest aid application will assist in determining the risks and costs of earlier applications (Wanjura and Newton, 1981).

CONCLUSIONS

Quantitative relationships of yield, micronaire, fiber maturity, fiber linear density, and neps (including the effect of lint cleaning) to crop condition at harvest aid application, with associated targets for optimizing these properties, will help in assessing risks and costs especially when earlier applications

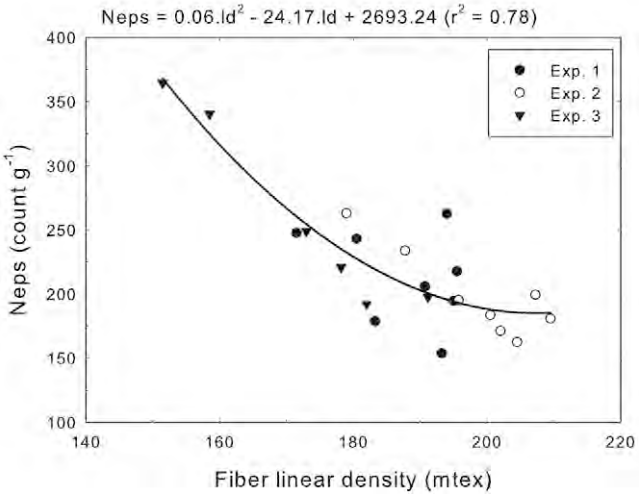

Fig. 4. The relationship that predicts the levels of neps (with no lint cleaning) with fiber linear density (ld).

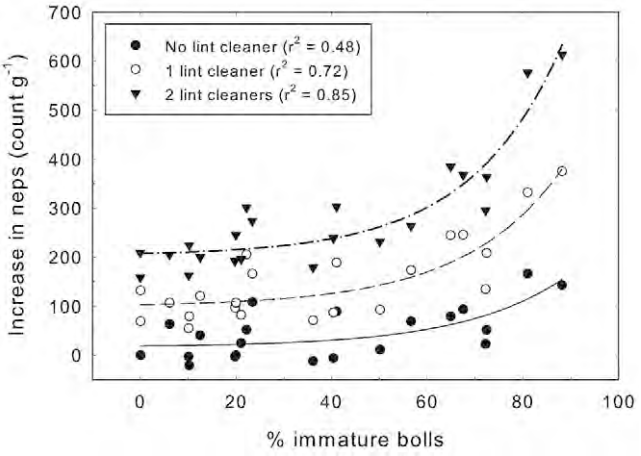

Fig. 5. An example of the response of change in lint neps with crop condition at harvest aid treatment associated with 0, 1, and 2 lint cleaning passes across all experiments. Change in neps is calculated as the change in neps from the control harvest aid treatment with no lint cleaning for each experiment. Regressions use a three parameter exponential function ($y = a \times e^{(bx)} + c$).

of harvest aids are considered. The percent immature bolls measure of crop condition utilizing the boll cutting technique predicted the effects of harvest aid timing and can be applied when crops are non-uniform in their maturity, such as when they contain a fruiting gap (Faircloth et al., 2004b). This however, will need to be evaluated along with a greater range of environments and cultivars, especially those cultivars differing in crop maturity where the degree of change in yield and aspects of quality such as micronaire can lead to differences in the response to harvest aid timing (Faircloth et al., 2004a). The addition of yield and quality data collected when there are more than 70% immature bolls at the tme of harvest aid application will help to strengthen the relationships developed in this study.

Recommendations for timing of harvest aid applications may also be better refined following detailed assessment of the textile performance (both yarn and fabric) of treatments that sequentially vary the quantity of immature fiber. The use of the percent immature lint mass derived in this study, along with the level of immature fiber in bolls defined using the boll cutting technique, may also help in predicting the textile consequences of immature fiber on neps and dye uptake in fabric generated from in-field and ginning practices. This is a subject of further research.

Table 5. Regression coefficients for effects of lint cleaning on change in nep levels (count g^{-1}). Change in neps is calculated as the change in neps from the control harvest aid treatment with no lint cleaning for each experiment. Regression used is a three parameter exponential function ($y = a \times e^{(bx)} + c$). Examples of fitted function are shown in Fig. 5. All regressions were significant at the 0.001 level.

Crop condition/No. of lint cleaning passes	r^2	*a*	*b*	*c*
Percent open bolls				
0 lint cleaning	0.41	115.08	–0.047	17.29
1 lint cleaning pass	0.64	237.53	–0.050	100.95
2 lint cleaning passes	0.70	342.24	–0.043	195.52
Percent immature bolls				
0 lint cleaning	0.48	2.11	0.047	16.81
1 lint cleaning pass	0.72	3.78	0.049	99.42
2 lint cleaning passes	0.85	4.30	0.052	203.22
Percent immature lint mass				
0 lint cleaning	0.50	0.45	0.078	21.15
1 lint cleaning pass	0.73	1.19	0.075	106.33
2 lint cleaning passes	0.87	0.55	0.091	216.78

ACKNOWLEDGMENTS

Thanks to Jane Caton, Darin Hodgson, Rebecca Giles, Sue Miller, and Geni Kozdra for assistance in the field and with AFIS measurements and Drs. Warwick Stiller and Geoff Naylor for helpful discussions about the results, and Cotton Seed Distributors for provision of planting seed. The Cotton Research and Development Corporation of Australia and the Cotton Catchment Communities Cooperative Research Centre both provided financial support for this work.

REFERENCES

Anthony, W.S., W.R. Meredith, and J.R. Williford. 1988. Neps in ginned lint: The effect of varieties, harvesting, and ginning practices. Text. Res. J. 58:633–639.

Bednarz, C.W., D.W. Shurley, and W.S. Anthony. 2002. Losses in yield, quality, and profitability of cotton from improper harvest timing. Agron. J. 94:1004–1011.

Bradow, J.M., G.H. Davidonis, O. Hinojosa, L.H. Wartelle, K.J. Pratt, K. Putsateri, P.J. Bauer, B. Fisher, G.F. Sassenrath-Cole, P.H. Dastoor, J.A. Landivar, D. Locke, and D. Moseley. 1996. Environmentally induced variations in cotton fiber maturity and related yarn and dyed knit defects. p. 2284–2290. *In* P. Dugger and D.A. Richter (ed.) Proc. Beltwide Cotton Conf., Nashville, TN. 9–12 Jan. 1996. Natl. Cotton Council of Am., Memphis, TN.

Brecke, B.J., J.C. Banks, and J.T. Cothren. 2001. Harvest-aid treatments: Products and application timing. p. 119–143. *In* J.R. Supak and C.E. Snipes (ed.) Cotton harvest management: Use and influence of harvest aids. The Cotton Foundation, Memphis, TN.

Cotton Seed Distributors. 2008. 2008 Variety guide. Wee Waa, New South Wales, Australia.

Dever, J.K., and J.R. Gannaway. 1988. Influence of cotton fiber strength and fineness on fiber damage during lint cleaning. Text. Res. J. 58:433–438.

Ethridge, M.D., and J. Simonton. 2004. Renewed focus on neps. Textile Topics Vol. 4. Int. Textile Ctr., Lubbock, TX.

Faircloth, J.C., K.L. Edmisten, R. Wells, and A.M. Stewart. 2004a. Timing defoliation applications for maximum yields and optimum quality in cotton containing a fruit gap. Crop Sci. 44:158–164.

Faircloth, J.C., K.L. Edmisten, R. Wells, and A.M. Stewart. 2004b. The influence of defoliation timing on yields and quality of two cotton cultivars. Crop Sci. 44:165–172.

Gordon, S.G. 2007. Cotton fiber quality. p. 68–100. *In* S.G. Gordon and Y-L Hsieh (ed.) Cotton: Science and technology. Woodhead Publ. Ltd., Cambridge, England.

Gordon, S.G., and N.L. Phair. 2005. An investigation of the interference colours transmitted by mature and immature cotton fiber under polarised light microscopy. p. 2284–2290. *In* P. Dugger and D.A. Richter (ed.) Proc. Beltwide Cotton Conf., New Orleans, LA. 4–6 Jan. 2005. Natl. Cotton Council of Am., Memphis, TN.

Gordon, S.G., M.H.J van der Sluijs, and M.W Prins. 2004. Quality issues for Australian cotton from a mill perspective. Australian Cotton Coop. Res. Centre, Narrabri, NSW.

Goynes, W.R., B.F. Ingber, and P.D. Bel-Berger. 1997. A simple method for detecting white speck potential in undyed cotton. p. 516–518. *In* P. Dugger and D.A. Richter (ed.) Proc. Beltwide Cotton Conf., New Orleans, LA. 7–10 Jan. 1997. Natl. Cotton Council of Am., Memphis, TN.

Hearn, A.B., and G.P. Fitt. 1992. Cotton cropping systems. p. 85–142. *In* C.J. Pearson (ed.) Ecosystems of the world—Field crop ecosystems. Elsevier, London.

Kerby, T.A., J. Supak, J.C. Banks, and C.E. Snipes. 1992. Timing defoliation using nodes above cracked boll. p. 155–157. *In* D.J. Herber and D.A. Richter (ed.) Proc. Beltwide Cotton Conf., Nashville, TN. 6–10 Jan. 1992. Natl. Cotton Council of Am., Memphis, TN.

Leffler, H.R. 1987. Mineral compartmentation within the boll. p. 301–309. *In* J.R. Mauney and J.M. Stewart (ed.) Cotton physiology: Number one. The Cotton Foundation, Memphis, TN.

Long, R.L., M.P. Bange, S.G. Gordon, and G.A. Constable. 2009. Measuring the maturity of developing cotton fibers using an automated polarized light microscopy technique. Text. Res. J. doi:10.1177/0040517509343784.

Mangialardi, G.J. 1985. An evaluation of nep formation at the cotton gin. Text. Res. J. 55:756–761.

Mangialardi, G.J., W.F. Lalor, D.M. Bassett, and R.J. Miravalle. 1987. Influence of growth period on neps in cotton. Text. Res. J. 57:421–427.

Naylor, G.R.S., and M. Purmalis. 2005. Update on Cottonscan: An instrument for rapid and direct measurement of fibre maturity and fineness. p. 2302–2306. *In* P. Dugger and D.A. Richter (ed.) Proc. Beltwide Cotton Conf., New Orleans, LA. 4–7 Jan. 2005. Natl. Cotton Council of Am., Memphis, TN.

Reid, P.E. 2003. Sicot 71. Plant Varieties J. 16:35–36.

Rochester, I.J. 2007. Nutrient uptake and export from an Australian cotton field. Nutr. Cycling Agroecosyst. 77:213–223.

Siebert, J.D., and A.M. Stewart. 2006. Correlation of defoliation timing methods to optimize cotton yield, quality, and revenue. J. Cotton Sci. 10:146–154.

Snipes, C.E., and C.C. Baskin. 1994. Influence of early defoliation on cotton yield, seed quality, and fiber properties. Field Crops Res. 37:137–143.

Thibodeaux, D.P., O. Hinojosa, and W.R. Meredith. 1993. Application of AFIS measurement technology to evaluating the quality of cotton treated with Prep™. p. 1113–1115. *In* D.J. Herber and D.A. Richter (ed.) Proc. Beltwide Cotton Conf., New Orleans, LA. 10–14 Jan. 1993. Natl. Cotton Council of Am., Memphis, TN.

Van der Sluijs, M.H.J., and L. Hunter. 1999. Neps in cotton lint. J.M. Layton (ed.). The Textile Inst., Manchester UK.

Wanjura, D.F., and O.H. Newton. 1981. Predicting cotton crop boll development. Agron. J. 723:476–481.

Fiber Quality and Textile Performance of Some Australian Cotton Genotypes

Robert L. Long,* Michael P. Bange, Stuart G. Gordon, Marinus H. J. van der Sluijs, Geoffrey R.S. Naylor, and Greg A. Constable

ABSTRACT

Improving the quality of Australian cotton fiber is essential for maintaining industry viability. Two field experiments were conducted to assess the fiber quality and yarn performance of Australian bred cotton (five *Gossypium hirsutum* L. and one *G. barbadense* L.) genotypes. The work included the novel measurement of fiber maturity ratio, fiber linear density, and fiber diameter (ribbon width). The strongest yarns were produced using genotypes with the longest and finest fiber, for example, the strength of 20 tex yarns for the *G. barbadense* L. cultivar Sipima 280 (length = 36.6 mm, linear density = 143 mtex, ribbon width = 13.7 μm) was 25.4 cN tex^{-1} cf. the *G. hirsutum* L. cultivar Sicala 350B (length = 32.5 mm, linear density = 185 mtex, ribbon width = 14.5 μm) yarn strength of 18.1 cN tex^{-1}. Micronaire was an inferior indicator of yarn performance, for example, the *G. hirsutum* L. breeding lines CHQX12B and CHQX377 each had micronaire values of 4.4, but CHQX377 spun stronger yarns due to its finer and more mature fiber. Lint cleaning had the greatest influence on nep (fiber knot) generation for *G. hirsutum* L. genotypes, generating on average 104 neps g^{-1} per lint cleaner passage. There was a negative association between fiber quality and yield, and a cost benefit analysis showed that fiber yield was the dominant economic factor compared to price premiums for better fiber quality. Alternative methods of determining fiber fineness will improve the value of Australian cotton.

R.L. Long, S.G. Gordon, M.H. J. van der Sluijs, G.R.S. Naylor, CSIRO Materials Science and Engineering, P.O. Box 21, Belmont, VIC, 3216, Australia. Cotton Catchment Communities Cooperative Research Centre. M.P. Bange, CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW, 2390, Australia. Cotton Catchment Communities Cooperative Research Centre. G.A. Constable, CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW, 2390, Australia. Received 19 Oct. 2009. *Corresponding author (robert.long@csiro.au).

Cotton is primarily grown for its fiber, and its popularity is due to the natural feel and light weight of cotton fabrics. Most Australian cotton (circa 98%) is exported and it has a good reputation based on consistency, low contamination, and adequate quality, and as such receives a premium on its base price (Australian Bureau of Agricultural and Research Economics 2008; The Australian Cotton Grower, 2008). However, the dynamic and ever increasingly competitive international market provides strong imperative for the Australian cotton industry to continue improving fiber quality to maintain market access for industry viability. Australian cotton represents approximately 10% of the medium to high grade volume in the export market (International Cotton Advisory Committee, 2008), and is used to produce medium to fine count (30 to 12 tex) yarns which are spun predominantly on ring spinning systems, of which 40 to 60% are combed yarns (Ratnam et al., 2005). These systems require good fiber length, strength, and fineness (smaller perimeter and thus with lower linear density) when compared to other spinning systems (Deussen, 1993); such quality parameters affect stronger yarns and enable finer yarns to be manufactured more efficiently (Fiori and Brown, 1951; Leitgeb and Wakeham, 1956). All Australian cotton is manually classed via U.S. Department of

Published in Crop Sci. 50 (2010).
doi: 10.2135/cropsci2009.10.0600
Published online 21 May 2010.

Agriculture (USDA) grade classification standards, and is objectively assessed using High Volume Instrument (HVI) testing for quality parameters (e.g., tensile and length properties).

In recent years there have been concerns by spinners relating to high micronaire and neps in some Australian cotton (Gordon et al., 2004). Micronaire is an air resistance based indirect measure of linear density that is influenced by both fiber perimeter and the degree of cell wall thickening or maturity (typically reported as maturity ratio) (Lord and Heap, 1988). It was intended to convey the intrinsic fineness (or coarseness) of cotton fiber. The original units for micronaire were micrograms per inch, but because a greater understanding of this technique has shown its unreliable representation of linear density alone, the measure is typically reported without units. The optimum range of micronaire is between 3.8 and 4.5 with discounts applied to growers when values fall outside this range. High micronaire cotton (>4.5) is considered coarse (large perimeter) by spinners and results in fewer fibers in the yarn cross-section, which translates into weaker and less even yarns. Yarn strength is recognized as the most important yarn quality attribute (May and Taylor, 1998; Ghosh et al., 2005). Due to the ever increasing competiveness and therefore low profit margins of textile manufacturing, fabric manufacturers require stronger yarns so they can produce fabric at maximum speed with minimal stoppages.

Neps are small entanglements of cotton fibers, especially immature or 'dead' fibers that develop during mechanical processing such as lint cleaning in the ginning process (Bogdan, 1954; Hebert et al., 1988; Mangialardi and Lalor, 1990). They are undesirable as they decrease mill processing efficiency and typically absorb less dye and reflect light differently, and may appear as 'flecks' on finished fabrics (Goynes et al., 1997; Anthony et al., 1988). While there is currently no routine testing of neps in Australian cotton and therefore no discount to growers, the high incidence of neps can affect overall industry reputation when cotton arrives at the mill. Gordon et al. (2004) reported that spinning mills prefer cotton to contain < 250 neps g^{-1}.

In delivering improved overall quality within an industry it is important to understand the contribution of all factors in the supply chain that limit quality. This includes differences attributed to genetics, management, and environment in which crops are grown, and processing and handling of cotton before delivery to the spinning mills. The strong influence that genetics has on fiber quality is well documented (Meredith et al., 1991; Saha et al., 2006; Asif et al., 2008) and unfortunately better quality is associated with lower yield (Green and Culp, 1990; Constable and Bange, 2007).

This study compares the fiber quality and textile performance of Australian cotton genotypes grown under standard commercial field growing conditions. Genotypes were a mix of commercially available cultivars and unreleased breeding lines with a range of fiber quality. The objective of this work was to ascertain how fiber quality differences led to changes in fiber neps and yarn performance of genotypes. This included the use of new instrumentation unique to the Australian industry to decipher the micronaire measure and to better determine the fineness (or coarseness) of cotton fiber. The cost benefits of premium quality vs. reduced yield were detailed and suggestions for a testing protocol for future genotype assessment was also an outcome of this work.

MATERIALS AND METHODS

Cultural Details of Field Experiments

Two field experiments were conducted over two consecutive growing seasons (2005/2006–Exp. 1 and 2006/2007–Exp. 2) at the Australian Cotton Research Institute (ACRI) at Narrabri (30°18' S, 149°48' E) to compare the quality and textile performance of Australian cotton genotypes. The location is a semiarid environment with gray vertosol (Isbell, 2002) in northwestern New South Wales, Australia. Both experiments used a randomized complete block design with genotypes as treatments with two replications. Logistics of handling large amounts of fiber for yarn processing limited the number of replications.

Genotypes bred by the Commonwealth Scientific and Industrial Research Organization (CSIRO) were used in these experiments, and included the commercially available *Gossypium hirsutum* L. (Upland) cultivars Sicot 71BR and Sicala 350B (Stiller, 2005), and the *G. barbadense* L. (Pima) cultivar Sipima 280 (Stiller, 2008). Experimental Upland breeding lines CHQX12B, CHQX377, and CHQX90 were also assessed. Sipima 280 and CHQX90 were only grown in Exp. 2. Sicot 71BR was the most widely grown Bollgard II/Roundup Ready (Monsanto Co., St. Louis, MO) cultivar, and was popular because of its high yields; in the 2005/2006 and 2006/2007 seasons Sicot 71BR occupied 21 and 41%, respectively, of the area grown to cotton in Australia. The other genotypes were evaluated as possible niche or premium fiber types. For example, Sicala 350B is a cultivar with significantly longer and finer fibers than Sicot 71BR, however its uptake by growers has been minimal due to its lower yields.

Experiments were sown with a disc opening Kinze commercial row-crop planter. Seeds were sown at 5 cm depth, delivered at 15 seeds m^{-1}. Experiment 1 was sown 25 Oct. 2005 while Exp. 2 was sown 17 Oct. 2006. Treatment plots were 180 m by eight rows in Exp. 1 and 585 m by three rows in Exp. 2; both had rows spaced at 1 m. Crops were established and grown with full irrigation, and using nonlimiting N applied as anhydrous ammonia (injected below and to the side of the plant line) at a rate of 200 kg ha^{-1} in Exp. 1 approximately 4 wk before sowing, and 180 kg ha^{-1} in Exp. 2, 8 wk before sowing. Crops were checked regularly for the presence of pests, which were controlled as required according to standard thresholds for non-Bollgard II cotton (Deutscher et al., 2004) and as described by Hearn and Fitt (1992). Experiments were defoliated in prep-

aration for harvest when all treatments had 80% of bolls open (Exp.1, 15 Apr. 2006; Exp. 2, 5 Apr. 2007).

Meteorological data for the experimental period was measured 2 km from the field site at the ACRI.

Harvest and Ginning

Experiments were machine harvested with a John Deere spindle cotton picker. Upland seed cotton was ginned on a Continental Eagle 100 saw gin with one lint cleaning passage, located at Cotton Seed Distributors, Wee Waa, New South Wales. Pima cotton was ginned with a Continental Eagle roller gin located at Clyde Agriculture, Bourke, New South Wales.

Fiber Quality Measurements

Following ginning, manual classing of fiber was undertaken to determine the color and leaf grades using USDA grade classification standards. Color grade is determined by the degree of reflectance and yellowness, while leaf grade is a visual estimate of the amount of cotton plant leaf particles in the ginned fiber.

Fiber samples were subjected to assessment using a Uster Technologies HVI model 900 to determine upper half mean length (mm), bundle strength (cN tex^{-1}), and micronaire. These represent measurements typically used in conjunction with manual classing results to determine any premiums or discounts applied by cotton merchants for cotton prices attained by growers.

Additional subsamples were blended through one passage of a SDL 'Shirley' Analyser Mk2, and then tested for maturity ratio using the CSIRO polarized light microscopy instrument SiroMat (Gordon and Phair, 2005; Long et al., 2009), gravimetrically determined linear density (mtex) using the CSIRO Cottonscan instrument (Naylor and Purmalis, 2005; Abbott et al., 2009), and fiber diameter (ribbon width) (μm) using the CSIRO photometric laser based instrument Sirolan-Laserscan (Lynch and Michie, 1976; Lunney and Irvine, 1979; Charlton, 1995). Resulting measurements for experimental units of fiber maturity ratio, linear density, and ribbon width were the average of three, five and three instrument replicates, respectively.

Neps (count g^{-1}) were measured using an Uster Technologies Advanced Fiber Information Systems (AFIS PRO) instrument. It is well known that the intense mechanical manipulation of the lint cleaner procedure in the ginning process is a major contributor of neps in cotton fiber (Anthony et al., 1988). Thus neps were measured not only in ginned fiber (following a single commercial lint cleaner passage for Upland and no lint cleaning for Pima) but also after Upland fiber had been subjected to additional experimental lint cleaner passages (an extra one–two lint cleaner passages in total, and an additional second pass–three lint cleaner passages in total). The CSIRO manufactured experimental lint cleaner had a sample feed loading density of 100 g m^{-2}, a saw speed of 855 rpm, a combing ratio (of the surface speed of the feed roller to the surface speed of the saw) of 23, and had four grid bars each located at a distance of 0.5 mm from the saw. Lint cleaning was performed in a cotton spinning mill with conditions of 23°C ± 2°C and 58% RH ± 2% RH. AFIS PRO neps measurements for each experimental sample were an average of five instrument replicates.

Yarn Manufacture

Fiber from field experiments was spun into yarn at CSIRO Materials Science and Engineering, Belmont, Victoria. For each experimental unit (bale), 50 kg of fiber was opened and cleaned via a Trützschler 'blowroom' which incorporated an Inclined Lattice Bale Feed and CVT3 Opener and Cleaner to remove trash and open the fiber. The fiber was then carded via a Trützschler DK 903 card to remove some short fibers, neps, and more trash. Carded sliver was then subjected to one passage of a Trützschler HSR 1000 draw frame, and the drawn sliver was then divided into two lots. One lot was subjected to a second draw frame passage (designated 'card') while the second lot was combed with a Vouk CM 400/S combing machine and then drawn a second time (designated 'combed'). The combing process further improves fiber straightening and alignment, and further removes short fibers, neps, and trash particles.

Both card and combed treatments were converted into twisted roving via a Zinser 660 FU roving machine. Twisted roving was spun on a Zinser 350 RM ring spinning machine to produce 20 tex yarns with a twist factor (αe) of 3.7 (792 turns per meter), which is considered a typical count yarn used for manufacturing light weight knitted fabrics. Thirty bobbins of yarn were produced for each genotype × replicate experimental unit.

Yarn Measurements

Yarn quality was tested for evenness [% coefficient of variation (% CV)] and yarn neps (+200%) using an Uster Technologies Uster Tester 4-SX, and for yarn strength (cN tex^{-1}) using a Zellweger Uster Uster Tensorapid 3. Yarn evenness is the measure of the variation in the mass of the yarn sampled every 10 cm for a 1000 m sample, yarn neps is the number of neps identified as being greater than twice the yarn thickness in a 1000 m sample, while yarn strength is the force required to break the yarn normalized to the linear density of the yarn. Measures of yarn quality are an average taken from 10 bobbins of yarn randomly selected from the 30 produced per processing treatment.

Data Analysis

Statistical differences in genotypes were analyzed using ANOVA and treatment means compared using Fisher's LSD method (5%).

RESULTS

Season Temperatures

Experiment 1 had warmer conditions than Exp. 2 through December and January, yet had cooler conditions than Exp. 2 at the end of the season (Fig. 1).

Fiber Yield

Over both seasons Sicot 71BR had the highest yields followed by CHQX12B then Sicala 350B. Yields of CHQX377 were similar to Sicala 350B in Exp. 1 but lower in Exp. 2. CHQX90 and Sipima 280 yields were lower than the other genotypes in Exp. 2 (Fig. 2).

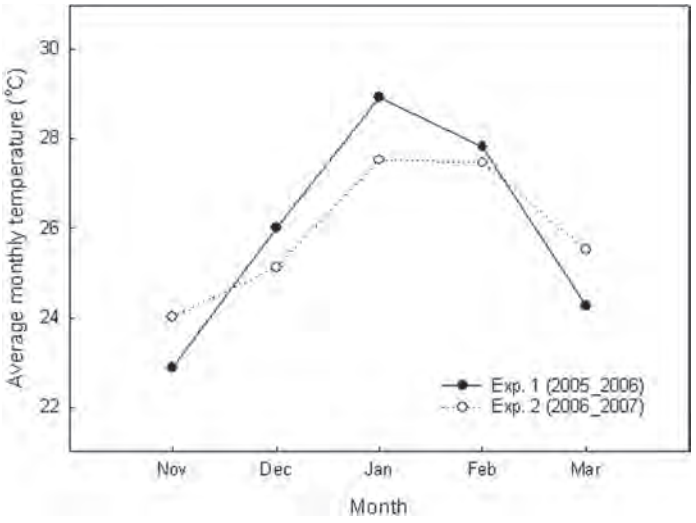

Fig. 1. Average monthly temperatures for both experiments.

Fiber Quality

Hand classing results showed little differences between Upland genotypes for either season, with color grade being Middling to Strict Middling at leaf grade 3. Pima was Middling (light spot) with a leaf grade of 2 (Table 1).

Fiber length differed between genotypes in both experiments (Table 1). Of the Upland genotypes Sicala 350B had the longest fibers, while Sicot 71BR had the shortest. The Pima cultivar had fibers substantially longer than all other genotypes (up to 6 mm longer than the Upland genotypes).

For fiber bundle strength, there were little differences in Exp. 1; in Exp. 2 Sicot 71BR was lower in strength. For the Upland genotypes in both experiments CHQX377 tended to have the highest fiber strength (Table 1). Fiber strength of Sipima 280 was substantially greater than the highest measured for the Upland genotypes (16.2 cN tex^{-1} strength units greater) (Table 1).

For micronaire there were no strong differences measured in Exp. 1, although Sicot 71BR trended to have higher micronaire. This result was reflected in small differences measured in maturity ratio, however, there were clear differences in fiber linear density with Sicot 71BR being significantly higher than the other genotypes (by 13

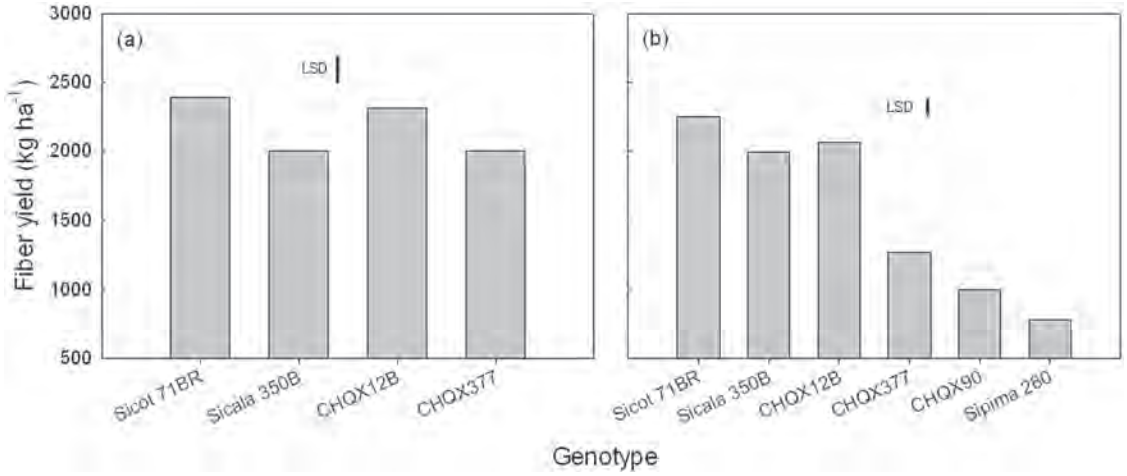

Fig. 2. Fiber yields of Australian cotton genotypes for (a) Exp. 1 (2005/2006) and (b) Exp. 2 (2006/2007). LSD values (P = 0.05) are reported for significant ANOVA results.

Table 1. Fiber quality attributes: High Volume Instrument determined length and strength, and manual class color and leaf grade for Exp. 1 (2005/2006) and Exp. 2 (2006/2007). Color and leaf grade based on USDA classification system. Color grade describes the degree of reflectance and yellowness (SM–strict middling; M–middling; LS–light spotted) while leaf grade a visual estimate of the amount of cotton plant leaf particles in the cotton on a scale from 1 (low) to 7 (high).

Genotype	Length		Strength		Color grade		Leaf grade	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
	mm		cN tex^{-1}					
Sicot 71BR	29.5	28.2	29.8	30.4	SM	SM	3	3
Sicala 350B	32.5	32.5	31.5	34.0	SM	SM	3	3
CHQX12B	32.0	31.2	32.0	33.2	SM/LS	M	3	3
CHQX377	31.0	31.5	34.0	35.4	SM	M	3	3
CHQX90	–	31.0	–	33.6	–	M	–	3
Sipima 280	–	36.6	–	51.5	–	M/LS	–	2
LSD	1.2**	0.8***	ns†	3.8***	–	–	–	–

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

†ns, not significantly different.

Table 2. Fiber micronaire (High Volume Instrument) including those attributes that influence it: fiber maturity (SiroMat polarized light microscope), gravimetrically determined fiber linear density (Cottonscan), and ribbon width (Sirolan-Laserscan); for Exp. 1 (2005/2006) and Exp. 2 (2006/2007).

Genotype	Micronaire		Maturity ratio		Linear density		Ribbon width	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
					mtex		µm	
Sicot 71BR	4.5	4.9	0.96	0.90	207	210	14.8	15.4
Sicala 350B	4.3	4.5	0.90	0.86	190	185	14.0	14.5
CHQX12B	4.4	4.7	0.89	0.85	199	192	14.7	15.2
CHQX377	4.4	4.4	0.95	0.83	192	174	13.9	14.3
CHQX90	–	4.0	–	0.80	–	168	–	14.5
Sipima 280	–	3.8	–	0.78	–	143	–	13.7
LSD	ns†	0.3***	ns	0.05*	11*	7***	0.2***	0.5**

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

†ns, not significantly different.

mtex) (Table 2). Ribbon width also varied with Sicot 71BR having the highest measured value along with CHQX12B (Table 2). In Exp. 2 micronaire differed with Sicot 71BR and CHQX12B having the highest values, while Sipima 280 had the lowest. These differences were reflected in the maturity ratio, linear density and ribbon width with Sicot 71BR also recording the highest values and Sipima 280 the lowest values of these measurements (Table 2).

Neps in Exp. 1 differed between genotypes with Sicot 71BR having the highest and CHQX377 having the lowest number of neps following one lint cleaning passage (Fig. 3a). Across genotypes lint cleaning significantly increased neps by an average of 104 neps per lint cleaner passage (i.e., an average of 190, 297, and 398 neps in fiber after one, two, and three lint cleaner passages, respectively) (Fig. 3b). In Exp. 2 there was less difference between the

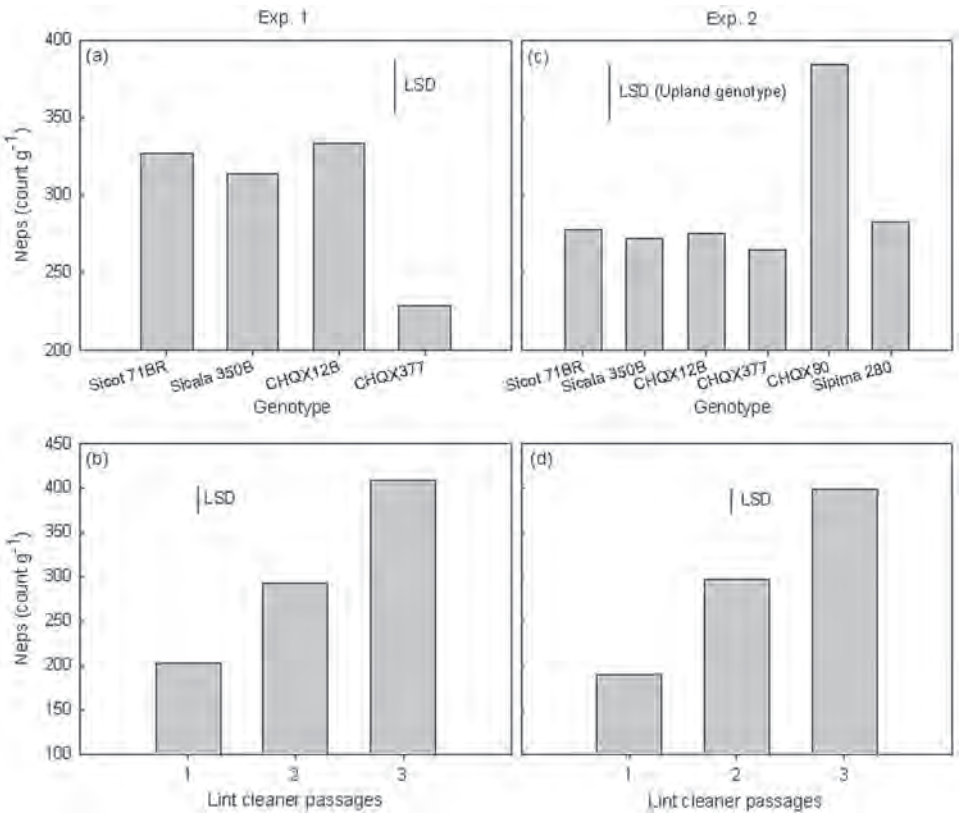

Fig. 3. Neps per gram of fiber measured with the Uster AFIS-PRO for (a and b) Exp. 1 (2005/2006) and (c and d) Exp. 2 (2006/2007). Upland genotypes were commercially saw ginned with one lint cleaner passage and then subjected to a second and third experimental lint cleaner treatment. The Pima cultivar Sipima 280 was commercially roller ginned and not subjected to any lint cleaning. LSD values ($P = 0.05$) are reported for significant ANOVA results (excludes Sipima 280); there was no significant interaction between genotype and lint cleaning.

Upland genotypes for neps with only CHQX90 having more neps than the others (Fig. 3c). Sipima 280 had more neps than all Upland genotypes with one lint cleaner passage (Fig. 3c). Again across the Upland cultivars lint cleaning increased neps by an average of 104 neps per lint cleaner passage (i.e., there was an average of 202, 292, and 409 neps in fiber following one, two, and three lint cleaner passages, respectively) (Fig. 3d). In both experiments there was no significant interaction between genotypes and the number of lint cleaning passages.

Yarn Quality

Yarn strength and evenness differed between genotypes in both experiments for carded and combed yarns, while yarn neps only differed across genotypes for Exp. 2 (Table 3). In Exp. 1 Sicot 71BR spun the weakest yarns, while CHQX377 spun the strongest carded yarns. For combed yarns Sicot 71BR had the lowest strength, but CHQX377 had similar strength to Sicala 350B (Table 3). Of the Upland genotypes in Exp. 2 Sicot 71BR had the lowest yarn strength while CHQX377 spun the strongest carded and combed yarns. Sipima 280 had substantially stronger yarns than any of the Upland cultivars; 6.2 and 7.0 cN tex^{-1} greater than CHQX377 for carded and combed yarns, respectively.

Yarn evenness in Exp. 1 for both carded and combed yarns was poorest for Sicot 71BR and CHQX12B, while Sicala 350B and CHQX377 spun more even yarns. In Exp. 2 Sicot 71BR and CHQX12B were less even than other genotypes for both carded and combed yarns, while CHQX377 and Sipima 280 spun the most even yarns (Table 3).

For carded yarn neps in Exp. 2, Sipima 280, CHQX90, and CHQX12B had more neps than the other genotypes. In combed yarns only Sipima 280 had more neps than the other genotypes which did not significantly differ from each other (Table 3).

Figure 4 summarizes the impacts of micronaire and its components (linear density and maturity ratio) and their effect on yarn strength. It shows that the lowest yarn strengths were associated with genotypes with fiber linear densities above 195 mtex. High micronaire values (≥4.5) were also associated with lower yarn strength with the exception of CHQX12B in Exp.1. Interestingly, three genotypes (CHQX377 for both experiments and CHQX12B for Exp. 1) had a micronaire of 4.4, but all varied in linear density and maturity ratio.

DISCUSSION

Yarn Performance

Genotypes with longer and finer fiber had higher bundle strengths and spun stronger and more even yarns. Yarn strength is greatly influenced by genotype and is the single most important yarn quality attribute (Meredith et al., 1991; May and Taylor, 1998). Of the Upland genotypes CHQX377 produced the strongest yarns (Table 3) and these were ranked in the top 25% of yarns currently manufactured (Uster Technologies, 2007). In comparison the strength of yarns made using Sicala 350B were in the 50% ranking, while Sicot 71BR was in the 75 to 95% ranking. The finer fibers of CHXQ377 meant there were more fibers in the yarn cross-section and thus significantly stronger yarns. The Pima cultivar spun the strongest yarns (Table 3) and these were ranked in the top 5%. Pima cotton exhibited fibers with the lowest linear density and ribbon width. Pima fibers were also significantly longer than the Upland genotypes. Fiber length contributes to greater inter fiber frictional forces and yarn strength.

The Importance of Measuring the Components of Micronaire

As detailed the degree of coarseness or fineness of cotton fiber has a significant influence on the number of fibers in a yarn cross-section (Pearson, 1955; Kloth, 1998; Bradow and Davidonis, 2000; El-Gaward, 2006). Fiber perimeter (or diameter when the fiber is circular) is the parameter that directly reflects fiber fineness (Wakelyn et al., 1998). However this parameter is challenging to determine, with the tedious cross-sectional method being the most direct technique (Hequet et al., 2006). Linear density relates well to fineness and the reason why micronaire is used as an index; the micronaire test is rapid and easy to conduct and samples hundreds of thousands of fibers in a 10-g sample. However micronaire better represents fiber bundle specific surface area than linear density alone, and is mathematically related to gravimetrically determined linear density and maturity ratio (Lord and Heap, 1988). Certainly our work highlights the potential inability of the micronaire measure; for Exp. 1 both CHQX12B and CHQX377 had the same micronaire and yet CHQX12B had coarse (higher linear density and ribbon width) and less mature fibers (Table 2, Fig. 4) and thus spun significantly weaker yarns (Table 3, Fig. 4). Similarly Sicot 71BR in Exp. 1 and Sicala 350B in Exp. 2 both had the same micronaire, but both had different linear density, maturity ratio, and yarn strength results (Fig. 4). Likewise, Raskopf (1966) reported that micronaire was a poor indicator of yarn strength.

Ribbon Width

The use of the Sirolan-Laserscan to measure ribbon width was a different approach of determining fiber fineness and its influence on yarn performance. Lord (1961) concluded that because ribbon width depends on both fiber perimeter and maturity, it cannot be regarded as a measure of intrinsic fiber fineness. Lord's method examined a small number of fibers via a manual microscopic technique which is likely to have been unrepresentative of a sample used for yarn manufacturing; no work is known that relates ribbon width to yarn performance. The Sirolan-Laserscan instrument examined up to about 3000 fiber snippets per experimental unit, and

significant differences in ribbon width were found between genotypes (Table 2). Interestingly, for a correlation analysis combining both season's data excluding the potential outlier effects of Sipima 280 (n = 9), ribbon width was better related to yarn strength than either micronaire or gravimetrically determined linear density, that is, fiber with smaller ribbon widths spun stronger yarns. However it should be noted that the genotypes in this study were all reasonably mature (i.e., the maturity ratio of the Upland genotypes was 0.80 or greater–Table 2) which may have minimized any confounding effects of maturity (wall thickening) over fiber perimeter effects on ribbon width. Seagull et al. (2000) measured fiber diameter and concluded that cotton fiber perimeter changed during development, although the authors probably measured the effects of fiber maturation on ribbon width; fiber perimeter was not measured directly and probably did not change. While linear density and maturity ratio may provide information about the physiological mechanisms effecting wall thickening and fineness (e.g., understanding a management practice on fiber maturity), an accurate measurement of ribbon width is likely to provide useful information about the outside dimensions of fibers that directly contribute to a yarn structure. Such information may add significant value to the modeling of yarn performance. Further studies are required to confirm the potential value of measuring cotton ribbon width.

Table 3. Yarn performance attributes of 20 tex ring spun carded and combed yarns for Exp. 1 (2005/2006) and Exp. 2 (2006/2007).

Genotype	Strength		Evenness		Neps	
	Exp. 1	Exp. 2	Exp. 1	Exp. 2	Exp. 1	Exp. 2
	cN tex^{-1}		CV%		+200%	
Carded Yarn						
Sicot 71BR	15.2	14.9	18.4	16.7	564	265
Sicala 350B	19.1	18.1	17.0	16.1	500	359
CHQX12B	16.7	16.9	18.2	17.4	522	586
CHQX377	19.9	19.2	16.7	15.2	457	336
CHQX90	–	17.2	–	16.5	–	554
Sipima 280	–	25.4	–	15.4	–	569
Combed Yarn						
Sicot 71BR	16.6	16.7	14.8	14.1	182	54
Sicala 350B	21.1	19.7	12.8	13.0	119	74
CHQX12B	19.8	18.3	13.9	13.5	154	86
CHQX377	21.3	20.4	13.7	13.1	70	63
CHQX90	–	19.4	–	12.8	–	84
Sipima 280	–	27.4	–	12.1	–	136
LSD Genotype	0.5***	0.5***	0.5**	0.4***	ns†	141*
LSD Card vs. Combed	0.3**	0.3***	0.4***	0.3***	32***	81***
LSD Interaction	ns	ns	ns	0.6**	ns	ns

* Significant at $P < 0.05$.

** Significant at $P < 0.01$.

*** Significant at $P < 0.001$.

†ns, not significantly different.

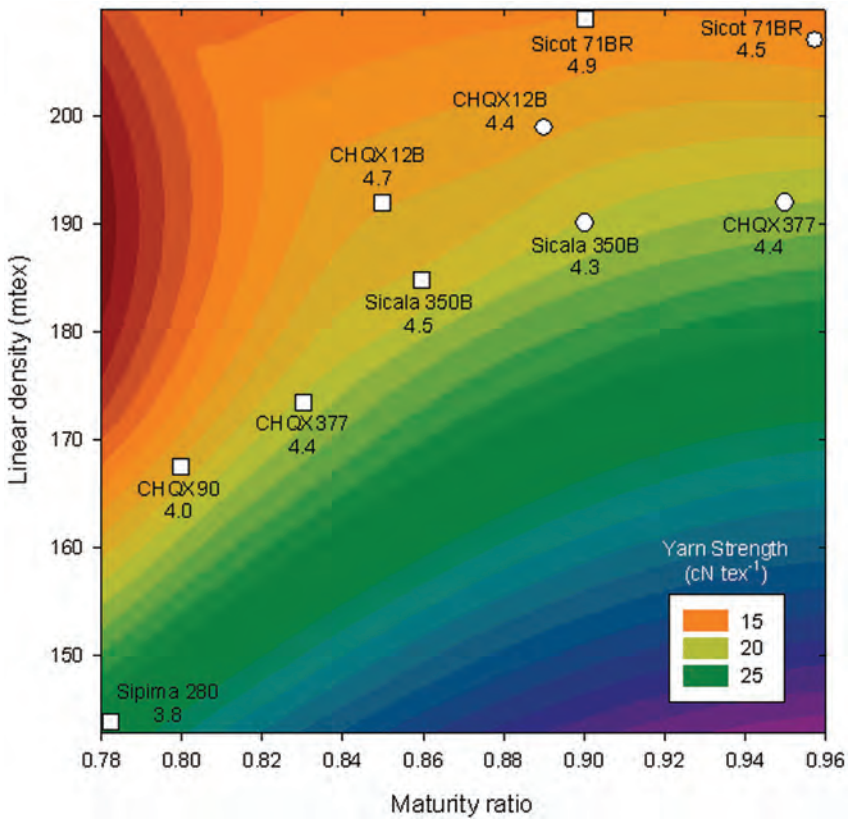

Fig. 4. Graphical representation of the effects of micronaire (values reported under genotype name) and its influencing components (linear density and maturity ratio) on carded 20 tex yarn strength for genotypes in Exp. 1 (2005/2006) (open circle) and Exp. 2 (2006/2007) (open rectangle). Chart is a 3D contour plot (linear model) created in SigmaPlot 10.0.

Neps

The relationship between fiber neps and yarn neps was poor for carded yarns, yet significant for combed yarns (for correlation analysis combining both season's data excluding Sipima 280, $n = 9$). This is attributed to differences in how fiber neps and yarn neps are determined. The AFIS PRO measures all neps in an opened fiber sliver, while yarn neps is a measure of imperfections on the yarn's surface which can be influenced by trash and dust (Peters, 2006). As well as removing large neps, the combing process would have also removed trash and dust, and aligned fibers, thus allowing a more effective determination of actual yarn neps.

Minimizing fiber neps minimizes neps problems in textile processing. To aid this cause a fiber neps quality maximum threshold of 250 neps g^{-1} for Upland and 190 neps g^{-1} for Pima has been suggested. These values are based on the Uster Statistics AFIS PRO neps levels, and cotton with these levels of neps will fall in the top 50% (or be better than average) (van der Sluijs and Hunter, 1999; Uster Technologies, 2007). The aim of this work was to identify genotypes with resilience to nep generation, and to understand the interaction between genotype and postharvest processes that are known to generate neps.

The strongest influence on neps was the mechanical action of saw lint cleaning which generated approximately 100 neps g^{-1} per lint cleaner passage (Fig. 3). The negative effects of lint cleaning on nep generation and fiber quality are well known (Griffin, 1979; Hebert et al., 1986; Anthony et al.,1988; Bange et al., 2010). The amount of lint cleaning and the lint cleaner mechanical configuration (e.g., saw speed and the number of grid bars) varies between gins and there has been considerable argument as to how much lint cleaning is appropriate, and the merits of cleaner cotton to obtain better classing grades vs. inferior fiber quality (Burley, 1959; Columbus et al., 1990).

The number of neps in Upland fiber in this study was similar to that observed by others; for example, Boykin (2008) reported average neps of 38 Upland cultivars with a single lint cleaner passage at 190 neps g^{-1} compared to 195 neps g^{-1} in this study (average of the nine Upland genotypes from Exp. 1 and 2 at a single lint cleaner passage). However additional lint cleaner passages (usually two) are common in commercial gins in Australia, and it is important to note that fiber subjected to two and three (experimental) lint cleaner passages displayed an average nep level greater than the maximum quality threshold of 250 neps g^{-1} (Fig. 3b, 3d).

No interaction was noted between Upland genotype and degree of lint cleaning, but some genotype differences in neps were evident. In Exp. 1 breeding line CHQX377 had the least propensity to generate neps (Fig. 3a). This was probably due to the high maturing nature of this genotype in relation to its lower linear density and smaller ribbon width (Table 2) in combination with its high bundle strength (Table 1); indeed van der Sluijs and Hunter (1999) reported that cotton with higher bundle strength will be less likely to break up and create neps. For Exp. 2, CHQX90's propensity to generate neps is attributed to this breeding line having low micronaire, maturity ratio and linear density in relation to a relatively larger ribbon width (Table 2); CHQX90 is coarse and less mature and therefore has less rigid weaker cell walls and thus a greater propensity to buckle and knot. The Pima cultivar had higher neps than expected (Fig. 3c) considering that no saw lint cleaning occurred during the roller ginning process. This can be attributed to the immaturity of the Pima cultivar (0.78 maturity ratio), which was low enough to allow the relatively gentler mechanical process in the roller gin (compared to saw ginning) to create neps. Pima cotton is normally grown under warmer environments than the Narrabri region, so the cooler temperatures during fiber maturation in Exp. 2 would have reduced fiber maturity in Pima.

Yield and Quality—Are Premium Cultivars Viable?

Yields in these experiments were similar or higher than the current Australian average yield (1991 kg ha^{-1}), and on average were approximately 2.8 times the world average yield (788 kg ha^{-1}) (The Australian Cotton Grower, 2008) (Fig. 2). As expected, over two seasons Sicot 71BR had the highest yield, Sicala 350B yielded 15% less and CHQX12B yielded 6% less. CHQX377 yielded similar to Sicala 350B in Exp. 1 but yielded less in Exp. 2; the marginally cooler growing conditions in Exp. 2 (Fig. 1) may have contributed to this reduction. CHQX90 and Sipima 280 yielded less than half that of Sicot 71BR (Fig. 2b).

As reported previously (Azhar et al., 2004; Constable and Bange, 2007) a negative association between fiber quality and textile performance, and yield was found. For example the lower yielding genotypes Sipima 280 and CHQX377 performed better than the higher yielding genotypes Sicot 71BR and CHQX12B. A basic economic analysis was conducted using the attributes in Table 1, micronaire (Table 2), yield (Fig. 2), the average premium-discount price points from six Australian merchant companies (data not shown), and assuming $350 and $700 per 227 kg bale for Upland and Pima, respectively. It was found that the premiums gained for better fiber quality attributes did not outweigh the loss of return due to decreased yield. Clearly with a 15% yield penalty (e.g., as for Sicala 350B), a premium fiber cultivar would need at least a 15% price premium and that is not always the case. Chiou et al. (1993) suggested that improvements in cotton quality would increase demand and enhance economic returns for the U.S. cotton industry, and likewise gradual improvements in quality and yield will ensure common Australian cotton remains competitive. Premium cultivars like Sicala 350B and Sipima 280 need to be on

hand should an economically viable niche market become available. For example, recent work has demonstrated the potential value of Sicala 350B to be used as a substitute for Pima cotton (van der Sluijs, 2007).

Protocols for Future Fiber Quality Assessment

Although it is generally conceded that micronaire is not necessarily the correct instrument to measure fineness/linear density or fiber maturity, its use continues with considerable impacts on price premiums/discounts. Routinely measuring the components of micronaire (maturity ratio and gravimetrically determined linear density) and or other measures of fineness (ribbon width) during classing, will ensure that discounts are applied appropriately, and is likely to offer economic value through the attraction of premium cultivars to niche markets by providing merchants and spinners with information which gives a more realistic indication of the potential textile performance of cotton.

The addition of AFIS PRO neps testing during classing would make growers aware of the production issues (cultivar and agronomic) effecting neps. Similarly the ginning industry would be in a better position to gin appropriately to minimize neps, while merchants could market cotton appropriately and potentially pay premiums for cotton with lower nep levels.

CONCLUSION

Australian cotton has a good reputation based on its consistency, low contamination, and adequate quality. The fiber and yarn performance of cotton genotypes bred by the CSIRO were assessed in two field experiments over two seasons, and included the use of novel instrumentation to measure fiber maturity ratio, fiber linear density, and ribbon width. All genotypes spun good quality yarns that would be accepted throughout international markets. Some genotypes had high fiber quality, although the financial premiums gained based on the current classing methodology did not outweigh the loss of return due to these genotypes having lower yield. Adopting new technology to better measure the components of micronaire and other measures of fiber fineness/coarseness (ribbon width) is likely to add value to Australian cotton and will aid in the development of better quality cotton genotypes.

Acknowledgments

We gratefully acknowledge Jane Caton, Darin Hodgson, Mark Freijah, Fred Horne, Susan Miller, Geni Kozdra, Nicole Phair-Sorensen, and Liz Coles for their excellent technical assistance. The authors thank Cotton Seed Distributors for provision of cotton seed as well as ginning the cotton. Much thanks goes to Clyde Agriculture and Australian Classing Services for their assistance. Funding was provided by the Cotton Research and Development Corporation, the Cotton Catchment Communities Cooperative Research Centre, and the CSIRO.

References

Abbott, A.M., G.J. Higgerson, R.L. Long, S.R. Lucas, G.R.S. Naylor, C.R. Tischler, and M.M. Purmalis. 2009. An instrument for determining the average fiber linear density (fineness) of cotton lint samples. Available at http://trj.sagepub.com/cgi/rapidpdf/0040517509348335v1.pdf (verified 23 Apr. 2010). Text. Res. J. doi:10.1177/0040517509348335.

Anthony, W.S., W.R. Meredith, and J.R. Williford. 1988. Neps in ginned lint: The effect of varieties, harvesting, and ginning practices. Text. Res. J. 58:633–640.

Asif, M., J.I. Mirza, and Y. Zafar. 2008. Genetic analysis for fiber quality traits of some cotton genotypes. Pakistan J. Bot. 40:1209–1215.

Australian Bureau of Agricultural and Resource Economics. 2008. Australian commodity statistics. Australian Bureau of Agricultural and Resource Economics, Canberra.

Azhar, F.H., M. Naveed, and A. Ali. 2004. Correlation analysis of seed cotton yield with fiber characteristics in *Gossypium hirsutum* L. Int. J. Agric. Biol. 6:656–658.

Bange, M.P., R.L. Long, G.A. Constable, and S.G. Gordon. 2010. Minimizing immature fiber and neps in upland cotton. Agron. J. 102:781–789.

Bogdan, J.F. 1954. Measurement of the nepping potential of cotton. Text. Res. J. 24:491–494.

Boykin, J.C. 2008. Seed coat fragments, motes, and neps: Cultivar differences. J. Cotton Sci. 12:109–125.

Bradow, J.M., and G.H. Davidonis. 2000. Quantitation of fiber quality and the cotton production-processing interface: A physiologist's perspective. J. Cotton Sci. 4:34–64.

Burley, S.T. 1959. A method for determining the effects of various gin treatments on the spinnability of cotton. Text. Res. J. 29:696–699.

Charlton, D. 1995. Sirolan-Laserscan. A review of its development, performance and application. Wool Technol. Sheep Breeding 43:212–228.

Chiou, G.T., D.T. Chen, and O. Capps. 1993. A structural investigation of biotechnological impacts on cotton quality and returns. Am. J. Agric. Econ. 75:467–478.

Columbus, E.P., P.D. Bel, and K.Q. Robert. 1990. Maintaining cotton quality. Trans. Am. Soc.Agric. Eng. 33:1057–1065.

Constable, G.A., and M.P. Bange. 2007. Producing and preserving fiber quality: From the seed to the bale. *In* Proc.: World Cotton Res. Conf. 4, Lubbock, TX. 10–14 Sept. 2007. CD-ROM, OmniPress_wcrc_40601. Paper 2168. Available at http:www.icac.org/meetings/wcrc/wcrc4/presentations/start.htm (verified 23 Apr. 2010). Int. Cotton Advisory Committee, Washington, DC.

Deussen, H. 1993. Rotor spinning technology. Schlafhorst, Charlotte, NC.

Deutscher, S.A., L.J. Wilson, and R. Mensah 2004. Integrated pest management guidelines for cotton production systems in Australia. The Australian Cotton Coop. Res. Centre, Narrabri, NSW.

El-Gaward, N.S.A. 2006. Measuring cotton fiber perimeter and wall thickness of some Egyptian cotton cultivars by using micromat tester. Egypt. J. Agric. Res. 84:147–152.

Fiori, L.A., and J.J. Brown. 1951. Effects of cotton fiber fineness on the physical properties of single yarns. Text. Res. J. 21:750–757.

Ghosh, A., S. Ishtiaque, S. Rengasamy, P. Mal, and A. Patnaik. 2005. Predictive models for strength of spun yarns: An overview. AUTEX Res. J. 5:20–29.

Gordon, S.G., and N.L. Phair. 2005. An investigation of the

interference colors in mature and immature cotton fibers. p. 2284–2290. *In* P. Dugger and D. Richter (ed.) Proc.: Beltwide Cotton Conf. National Cotton Council, New Orleans, LA.4–7 Jan. 2005. Natl. Cotton Council, Cordova, TN.

Gordon, S.G., M.H.J. van der Sluijs, and M.W. Prins. 2004. Quality issues for Australian cotton from a mill perspective. Australian Cotton Coop. Res. Centre, Narrabri, NSW.

Goynes, W.R., B.F. Ingber, and P.D. Bel-Berger. 1997. A simple method for detecting white speck potential in undyed cotton. p. 516–518. *In* Proc. Beltwide Cotton Conf., New Orleans, LA. 7–10 Jan. 1997. Natl. Cotton Council of Am., Memphis, TN.

Green, C.C., and T.W. Culp. 1990. Simultaneous improvement of yield, fiber quality, and yarn strength in upland cotton. Crop Sci. 30:66–69.

Griffin, A.C. 1979. High capacity ginning and fiber breakage. Text. Res. J. 49:123–126.

Hearn, A.B., and G.P. Fitt. 1992. Cotton cropping systems. p. 85–142. *In* C.J. Pearson (ed.) Ecosystems of the world-Field crop ecosystems. Elsevier, London.

Hebert, J.J., E.K. Boylston, and D.P. Thibodeaux. 1988. Anatomy of a nep. Text. Res. J. 58:380–382.

Hebert, J.J., G. Mangialardi, and H.H. Ramey. 1986. Neps in cotton processing. Text. Res. J. 56:108–111.

Hequet, E.F., B. Wyatt, N. Abidi, and D.P. Thibodeaux. 2006. Creation of a set of reference material for cotton fiber maturity measurements. Text. Res. J. 76:576–586.

International Cotton Advisory Committee. 2008. World textile demand. Int. Cotton Advisory Committee, Washington, DC)

Isbell, R.F. 2002. The Australian soil classification. CSIRO Publ., Melbourne.

Kloth, R.H. 1998. Cotton improvement–Analysis of commonality traits of cotton fiber. J. Cotton Sci. 2:17–22.

Leitgeb, D.J., and H. Wakeham. 1956. Cotton quality and fiber properties part v: Effects of fiber fineness. Text. Res. J. 26:543–552.

Long, R.L., M.P. Bange, S.G. Gordon, and G.A. Constable. 2009. Measuring the maturity of developing cotton fibers using an automated polarized light microscopy technique. Available at http://trj.sagepub.com/cgi/content/abstract/80/5/463 (verified 23 Apr. 2010). Text. Res. J. 80(5):463–471. doi 10.1177/0040517509343784.

Lord, E. 1961. The characteristics of raw cotton. The Textile Inst. Butterworths, Manchester.

Lord, E., and S.A. Heap. 1988. The origin and assessment of cotton fibre maturity. Int. Inst. for Cotton, Manchester.

Lunney, H.W.M., and P.A. Irvine. 1979. Some factors affecting measurement by the CSIRO fiber-fineness distribution analyser. Text. Res. J. 49:371–379.

Lynch, L.J., and N.A. Michie. 1976. An instrument for the rapid automatic measurement of fiber fineness distribution. Text. Res. J. 46:653–660.

Mangialardi, G.J., and W.F. Lalor. 1990. Propensity of cotton varieties to neppiness. Trans. Am. Soc. Agric. Eng. 33:1748–1758.

May, O.L., and R.A. Taylor. 1998. Breeding cottons with higher yarn tenacity. Text. Res. J. 68:302–307.

Meredith, W.R., T.W. Culp, K.Q. Robert, G.F. Ruppenicker, W.S. Anthony, and J.R. Williford. 1991. Determining future cotton variety fiber quality objectives. Text. Res. J. 61:715–720.

Naylor, G.R.S., and M. Purmalis. 2005. Update on Cottonscan: An instrument for rapid and direct measurement of fiber maturity and fineness. p. 2302–2306. In P. Dugger and D. Richter (ed.) Proc.: Beltwide Cotton Conf., New Orleans, LA. 4–7 Jan. 2005. Natl. Cotton Council, New Orleans, LA.

Pearson, N.L. 1955. A study of cotton fiber perimeters as calculated from arealometer values at low and high compression. Text. Res. J. 2:124–136.

Peters, G. 2006. Application report–The correlation between fiber neps and yarn neps. Uster Technologies AG, Uster, Switzerland.

Raskopf, B.D. 1966. Micronaire tests for cotton and cotton quality relationships. The Univ. of Tennessee Agric. Exp. Stn., Knoxville.

Ratnam, T.V., I. Doraiswamy, and K.P. Chellamani. 2005. Quantitative requirements of cotton by 2010. Asian Textile J. (October 2005):88.

Saha, S., J.N. Jenkins, J. Wu, J.C. McCarty, O.A. Gutierrez, R.G. Percy, R.G. Cantrell, and D.M. Stelly. 2006. Effects of chromosome-specific introgression in upland cotton on fiber and agronomic traits. Genetics 172:1927–1938.

Seagull, R.W., V. Oliveri, K. Murphy, A. Binder, and S. Kothari. 2000. Cotton fiber growth and development 2. Changes in cell diameter and wall birefringence. J. Cotton Sci. 4:97–104.

Stiller, W.N. 2008. Sipima 280. Plant Var. J. 21:112.

Stiller, W.N. 2005. Sicala 350B. Plant Var. J. 19:76–80.

The Australian Cotton Grower. 2008. Cotton year book. The Australian Cotton Grower 29:1–160.

Uster Technologies. 2007. Uster statistics. Uster Technologies AG, Uster, Switzerland.

van der Sluijs, M.H.J. 2007. Blending could add value to long staple Upland varieties. The Australian Cotton Grower 28:34–38.

van der Sluijs, M.H.J., and L. Hunter. 1999. Neps in cotton. Textile Progress 28:1–51.

Wakelyn, P.J., N.R. Bertoniere, A.D. French, S.H. Zeronian, T.P. Nevell, D.P. Thibodeaux, E.J. Blanchard, T.A. Calamari, B.A. Triplett, and C.K. Bragg. 1998. Cotton fibers. p. 577–724. *In* M. Lewin and E.M. Pearce (ed.) Handbook of fiber chemistry. Marcel Dekker, New York.

The *Journal of Cotton Science 14:164–172 (2010)*
http://journal.cotton.org, © The Cotton Foundation 2010

MOLECULAR BIOLOGY AND PHYSIOLOGY

A Method to Estimate the Effects of Temperature on Cotton Micronaire

Michael P. Bange*, Greg A. Constable, David B. Johnston, and David Kelly

ABSTRACT

Differences in micronaire of cotton fiber can affect grower returns, and influence textile quality. Therefore quantifying those effects that influence micronaire are important in developing management practices to optimise micronaire. This study proposes a method for predicting seasonal crop micronaire. The aim was to quantify the response of micronaire to temperature during boll filling and assess this information's ability to predict micronaire on an independent dataset. Utilising existing data from sowing time experiments in Australia that spanned three decades, linear responses of micronaire to both daily average and minimum temperatures were developed (r^2 =0.68 for both). These responses coupled with an estimate of temperature during the boll filling period when the majority of bolls were undergoing fiber thickening were able to successfully predict the micronaire on an independent dataset (r^2=0.42) despite no adjustment for other climate and management factors that may influence crop micronaire. The ability to predict temperature effects on micronaire will be useful to assess reasons for seasonal and regional differences in micronaire and assess opportunities to modify micronaire with changes in management practices that influence the timing of boll development.

Micronaire (no units) of cotton is a fiber quality trait that reflects a combination of fiber linear density (often referred to as fineness) and fiber maturity (Lord and Heap, 1988). Too high micronaire (> 4.5) may indicate that fiber is coarse and is undesirable for spinners as it results in too few fibers in yarn cross section, reducing its strength. Too low micronaire (< 3.8) may mean that fibers are immature, leading to breakages in fibers within the yarn and poor dye uptake during textile processing. As a consequence growers may incur price discounts if micronaire of their cotton falls outside the optimal range (3.8 to 4.5) (Bange et al., 2009; Bednarz et al., 2002; Gordon and Naylor, 2004).

The degree of fiber thickening or fiber maturity, contributes to differences in micronaire. When comparing fibres of similar perimeter the thicker the layers of cellulose laid down the more mature the fiber, and the higher the micronaire. Since fiber is primarily cellulose any influence on net crop photosynthesis and carbohydrate production will have similar influence on fiber thickening.

It therefore stands to reason that as photosynthesis is highly influenced by temperature (El-Sharkawy and Hesketh, 1964); sustained changes in temperature during the fiber thickening period will lead to differences in micronaire. In addition, studies of cotton fiber development using cultured cotton ovules have shown that cool temperatures during secondary wall thickening affected cellulose deposition leading to differences in fiber weight (Haigler et al., 1990; Roberts et al., 1992). These studies provided evidence to suggest that temperature influences on fiber development were also ovule specific during this phase, and was not entirely dependent on carbohydrate supply; reinforcing the significant effects of temperature on micronaire.

Many studies have shown that micronaire responds to temperature changes (Gipson and Joham, 1968; Hesketh and Low, 1968; Gipson and Ray, 1970; Wanjura and Baker, 1985; Liakatas et al., 1998; Reddy et al., 1999). Radiation (Pettigrew, 1995; Wang et al., 2006); plant defoliation (Siebert et al., 2006; Bange et al., 2010); water stress (Hearn, 1994); and competition among bolls for carbohydrate within the plant (Brook et al., 1992; Pettigrew, 1995), have also been shown to affect micronaire. A fundamental understanding

M.P. Bange*, G.A. Constable, and D.B. Johnson, CSIRO Plant Industry, Locked Bag 59, Narrabri NSW 2390 Australia; D. Kelly, Cotton Seed Distributors, PO Box 1121, Goondiwindi QLD 4390 Australia
*Corresponding author: Michael.Bange@csiro.au

of the degree of these influences on micronaire is important so that management practices can be developed to optimise micronaire.

Wanjura and Supak (1985) have used this understanding to predict or analyse consequences of temperature on micronaire. In this paper an alternative approach for predicting seasonal crop micronaire is proposed and tested. The response of micronaire to temperature was developed from micronaire measured from sowing time studies, and the use of a new approach to estimate the temperature during the fiber thickening phase of a crop's boll filling period was used. The ability of this approach to predict micronaire was tested against an independent dataset. This approach can be utilised to predict or analyse the effects on seasonal temperatures on micronaire such that management decisions may be refined to improve micronaire.

MATERIALS AND METHODS

Estimating temperature effects on micronaire. Fiber development for an individual boll occurs between flowering and boll maturity (defined as a cracked boll). This period is often referred to as the boll period. Fiber development during the boll period can be divided into three phases: fiber elongation, secondary wall thickening, and maturation (Ryser, 1999). For *Gossypium hirsutum,* fiber elongation occurs over approximately 20 d (Gipson and Joham, 1968; Gipson and Ray, 1969; Benedict et al., 1973; Meinert and Delmer, 1977), but this period can vary with temperature (Gipson and Joham, 1968, 1969; Gipson and Ray, 1969). Fiber thickening leading to differences in micronaire occurs over a period of approximately 40 d (Shubert et al., 1973; Benedict et al., 1973) following fiber elongation and similarly varies with temperature (Gipson and Joham, 1968).

To estimate the period of fiber elongation and fiber thickening leading to differences in micronaire, thermal time of an average boll period of 68 d (750 day degrees (DD)) (Constable, 1991; Hearn and Constable, 1984; Constable and Shaw, 1988) was divided proportionally using 20 d for fiber elongation and the following 40 d for fiber thickening. This equates to a 220 DD for the fiber elongation period and 440 DD for the fiber thickening phase. The remaining time is considered the fiber maturation phase in which the fibers dry, causing the vacuole (lumen) to collapse and the fiber to die.

Fiber quality data for these studies came from multisite experiments over a number of seasons. In order to determine any relationship between micronaire and temperature, it was necessary to retrospectively estimate development as above. Micronaire was compared with temperatures during mid boll fill, specifically from about 1200 to 1440 DD from sowing. These dates were chosen to represent the stage when the majority of bolls in a crop were estimated to be at the fiber thickening stage. Some earlier bolls would not have reached fiber thickening at 1200 DD and some later bolls may still be thickening after 1440 DD. Those points in development were chosen as follows:

The start of flowering was estimated as 777 DD (Constable, 1991) after sowing. Cold shocks delay flowering when minimum temperature reaches or falls below 11°C (Hearn and Constable, 1984). It was assumed that these crops required ten fruiting nodes to contribute to the majority of yield (Constable, 1991). The mid point of flowering was therefore five nodes after first flower (at 42 DD per node, or 210 DD). Since fiber elongation occurs in the first 220 DD after flowering, the point when all bolls have reached the fiber thickening stage is 777+210+220 = 1197 DD. Fiber thickening is complete for the first bolls when 777+660 = 1437 DD. From that point, successive bolls are mature, and the period when all bolls are thickening ceases. Daily average and minimum temperature are then calculated for this fiber thickening period.

Day degrees (DD) were derived using a base temperature of 12°C (Constable and Shaw, 1988):

$$\text{Day degrees} = \left[\left(T_{\max} - 12\right) + \left(T_{\min} - 12\right)\right] / 2 \qquad (1)$$

where T_{max} and T_{min} are daily maximum and minimum temperatures respectively. When $T_{min} <$ 12°C, $T_{min} = 12$. (or $(T_{min} - 12) \geq 0.0$).

Response of micronaire to temperature. To develop a relationship to temperature during the boll filling period of crop development measurements from sowing time experiments were utilised. These studies were grown with full nutrition and water requirements with sowing time, season, and location, all contributing to differences in temperature experienced by the crop during boll filling. Details of each experiment are presented in Table 1.

Table 1. Details of sowing time experiments used to generate the responses of micronaire to temperature. Origin of all cultivars are from CSIRO† Australia unless specified. Average cultivar micronaire values were measured by CSIRO's cotton breeding program long term dataset. With the exception of the study by Constable et al. where micronaire was measured using an areolometer, all other micronaire measurements were measured using a High Volume Instrument (HVI). The highest and lowest daily average minimum and maximum temperatures recorded for each experiment are also shown. These temperatures were estimated using the approach proposed in this paper.

Year Sown	Location	Sowing dates	Cultivars	First Flower Measured	Published	Average Min. Temperature (˚C)	Average Max. Temperature (˚C)	Average Cultivar Micronaire
1969 1971 1972	Narrabri	Sep. 30, Oct. 10, Oct. 20, Oct. 30, Nov. 10, Nov. 20, Nov. 30	DP Smoothleaf (Deltapine USA), Short Sympodial	No	Constable et al. (1976) (1)‡	13.4 13.4 17.5	32.6 30.1 32.8	3.95
2002	Narrabri	24 Sep., 15 Oct., 11 Nov.	Sicot 189 Sicot 289B	Yes	Bange et al. (2008) (2)	17.8	36.4	4.19 4.49
2002	Hillston	27 Sep., 24 Oct., 27 Nov.	Sicala S40i Siokra V-16i	No	Bange et al. (2004) (3)	15.0	34.9	4.16 3.97
2002	Breeza	25 Sep., 16 Oct., 18 Nov.	Siokra S101i Sicala V3i	Yes	Unpublished (4)	12.6	33.5	3.97 3.98
2003	Narrabri	13 Oct., 5 Nov., 28 Nov.	Sicot 189R Sicot 289BR	Yes	Bange et al. (2008) (5)	15.7	34.9	4.04 4.29
2003	Breeza	26 Sep., 14 Oct., 4 Nov.	Sicala 43 Sicala 43B	No	Unpublished (6)	17.8	32.9	4.26 4.30
2004	Narrabri	6 Oct., 22 Oct., 28 Nov.	Sicot 189R Sicot 289BR	Yes	Bange et al. (2008) (7)	17.9	34.1	4.04 4.29
2004	Breeza	28 Sep., 14 Oct., 27 Oct.	Sicala V3BR Sicala 60BR	Yes	Unpublished (8)	14.5	33.8	4.16 4.47
2007	Narrabri	16 Oct., 13 Nov.	Sicot 71BR Sicot 70BRF Sicot F1BRF	Yes	Unpublished (9)	12.9	30.4	4.50 4.13 4.37
2008	Narrabri	16 Oct., 14 Nov.	Sicot 71BR Sicot 70BRF Sicot F1BRF	Yes	Unpublished (10)	15.7	32.8	4.50 4.13 4.37

†CSIRO (Commonwealth Scientific and Industrial Research Organisation Australia).

‡Number in parenthesis specifies the dataset label used in the micronaire versus temperature responses in Fig. 1.

For each treatment of each experiment, daily average and minimum temperature during boll development were derived using the methodology described above. For the Narrabri location, climate data was obtained using records from the Australian Cotton Research Institute. For other locations, climate data was obtained from records from the nearest major town to the experiment site using the SILO patched point dataset (Jeffrey et al., 2001) that uses Australian Bureau of Meteorology official weather stations. Where experiments recorded the date on which first flower occurred, this information was used to initiate the time when temperature was estimated, otherwise timing of first flower was predicted, as described above.

Micronaire for each sowing treatment (averaged across cultivars) for each experiment was then regressed with the derived daily average and minimum temperature. Regression analysis was used to fit both linear and quadratic functions (Sigma Plot ver. 11, Systat Software, Inc., San Jose, California). Relative improvement of the quadratic response over the linear response was tested using F-tests based on residual means squares (RMS) accounting for differences in the function's degrees of freedom (Cousens, 1985).

Predicting micronaire from temperature. For validation purposes micronaire was compiled for a number of commercial cultivars grown in cultivar evaluation studies undertaken by Cotton Seed Distributors (CSD). The cultivars were grown across a range of sites in existing cotton regions in Australia from southern New South Wales (NSW) to central Queensland (Qld) in crops sown from 2000 to 2007.

Micronaire from four CSIRO cultivars was compiled; Sicot 71, Sicot 71B, Sicot 71BR, and Sicot 71 BRF. These were chosen because they were the most widely grown commercially across regions

and years. The average micronaire of these cultivars obtained from the CSIRO's cotton breeding program long-term dataset were: 4.25 for Sicot 71; 4.38 for Sicot 71B; 4.5 for Sicot 71BR; and 4.13 for Sicot 71BRF. Details of cultivar evaluation data used are presented in Table 2.

For each cultivar grown at each site and every year, temperature during boll development was calculated using the approach for temperature estimation described previously. Climate data was again obtained from the SILO patched point dataset (Jeffrey et al., 2001) for the nearest major weather station (< 50 km).

Table 2. Details of information used for micronaire prediction validation from Cotton Seed Distributors (CSD) (Wee Waa, NSW, Australia) cultivar evaluation sites. The range of years in which the cultivar evaluation was conducted and number of sites (in brackets) is shown under respective cultivars. For example 01-05(5) means that the cultivar was evaluated between 2001 and 2005 at five sites in the location specified.

Location	State	Latitude / Longitude	Cultivar			
			Sicot 71	Sicot 71B	Sicot 71BR	Sicot 71BRF
Emerald	Qld	148.2/ -23.5	01-05(5)	05-07(5)	03-07(8)	07(2)
Moura	Qld	150.0/ -24.6		05-06(2)	06(1)	
Theodore	Qld	150.1/ -25.0	02-03(2)	07(1)	04-07(6)	07(2)
Byee	Qld	151.8/ -26.2			04-05(2)	
Murgon	Qld	151.9/ -26.2		05(1)		
Macalister	Qld	151.1/ -27.0		07(1)	04-07(4)	07(2)
Dalby	Qld	151.3/ -27.2	00-04(5)	06-07(2)	04-07(3)	07(2)
Cecil Plains	Qld	151.2/ -27.5		06-07(2)		07(1)
Bongeen	Qld	151.4/ -27.6				07(1)
Brookstead	Qld	151.4/ -27.8	01-02(3)	05(1)	06-07(2)	07(1)
St George	Qld	148.6/ -28.0	00-06(7)	06-07(2)	03-07(8)	07(2)
Toobeah	Qld	149.9/ -28.4				07(1)
Dirranbandi	Qld	148.2/ -28.6	00-03(3)	05(1)	04-06(2)	
Goondiwindi	Qld	150.3/ -28.6	00-06(10)	07(1)		
Boggabilla	NSW	150.4/ -28.6		05-07(2)	04-07(5)	07(1)
Mungindi	NSW	149.0/ -29.0	01-07(5)	05-06(2)	03-06(6)	07(1)
Collarenebri	NSW	148.6/ -29.5		06(1)	05(1)	
Moree	NSW	149.8/ -29.5	00-06(12)	05(4)	03-07(13)	06-07(6)
Walgett	NSW	148.1/ -30.0	01-04(3)		04-06(4)	
Bourke	NSW	145.9/ -30.1	00-04(3)		03-05(4)	
Wee Waa	NSW	149.4/ -30.2	01-07(5)	05(1)	03-07(7)	07(2)
Narrabri	NSW	149.8/ -30.3	00-01(3)		03-06(3)	07(1)
Boggabri	NSW	150.0/ -30.7		05-07(2)	03-07(5)	07(1)
Gunnedah	NSW	150.3/ -31.0	01-04(4)			
Breeza	NSW	150.5/ -31.2	01-03(3)		02-07(7)	07(2)
Warren	NSW	147.8/ -31.7	01-05(4)		04-06(4)	
Trangie	NSW	148.0/ -32.0			04-06(4)	07(1)
Narromine	NSW	148.2/ -32.2	01-03(3)		03-05(2)	
Menindee	NSW	142.4/ -32.4	01-05(3)	05(1)	04-05(2)	
Hillston	NSW	145.5/ -33.5	01-07(7)		04-07(7)	07(2)
Hay	NSW	144.9/ -34.5			04-05(2)	

Sowing time of the CSD cultivar evaluation studies was the only variable needed to predict daily average and minimum temperatures. These temperatures were then used to estimate micronaire from the linear responses of micronaire to daily average and minimum temperatures.

To assess the performance of this approach to predict micronaire, predicted micronaire was plotted against the measured (observed) micronaire. Accuracy of predictions was quantified using the root mean square deviation (RMSD) between a number (n) of predicted (P) and observed (O) paired results:

$$RMSD = \left[\sum (O-P)^2 / n\right]^{0.5}$$ (Steele and Torrie, 1987)

RMSD represents a mean weighted difference between predicted and observed data. The linear regression of predicted versus observed values was used to quantify bias and the coefficient of determination (r^2) of this regression described the degree to which the data clustered around a straight line. Linear regression analyses were conducted using Sigma Plot (ver. 11, Systat Software, Inc., San Jose, California).

In an attempt to improve accuracy of prediction, inherent differences in micronaire (Mic_{adj}) of the cultivars were considered. Predicted micronaire was adjusted using the using the weighted average (micronaire 4.4) of the cultivars used to generate the micronaire versus temperature responses (Table 1), and the average micronaire of cultivars (Mic_{cuv}) used in the validation:

$$Mic_{adj} = Mic_{pred} - (4.4 - Mic_{cuv})$$

where Mic_{pred} is the predicted micronaire unadjusted for cultivar differences. The performance of this adjustment was assessed similar to micronaire predictions unadjusted for cultivar.

RESULTS AND DISCUSSION

Response of micronaire to temperature. Despite differences in cultivars that spanned three decades, micronaire was strongly related to average temperature that was estimated using the methodology detailed in this paper. Both the average of the daily minimum and average temperatures experienced during the period of fiber thickening contributing to final micronaire were similar in explaining changes in micronaire across all sowing times ($r^2 = 0.68$; Table 3; Fig. 1). The use of quadratic functions slightly improved r^2, but the improvement was not significant ($P < 0.05$) (Table 3). All experiments fitted the same regression.

Table 3. Results of regression analyses of micronaire versus daily average temperature and daily minimum temperature averaged for the estimated period of fiber thickening. Data used in this analysis is detailed in Table 1. Linear ($y = bx + c$) and quadratic regressions ($y = ax^2 + bx + c$) were tested for each variable. All regressions were highly significant ($P < 0.001$, $n = 46$). RMS – Residual Mean Squares for the fitted models.

Regression type and variable tested	r^2	*a*	*b*	*c*	RMS
Linear -Average daily temperature	0.68	-	0.19	-0.53	0.0722
Quadratic - Average daily temperature	0.69	0.81	-0.01	-7.99	0.0699
Linear - Minimum daily temperature	0.68	-	0.16	1.29	0.0726
Quadratic - Minimum daily temperature	0.70	0.48	-0.009	-1.40	0.0696

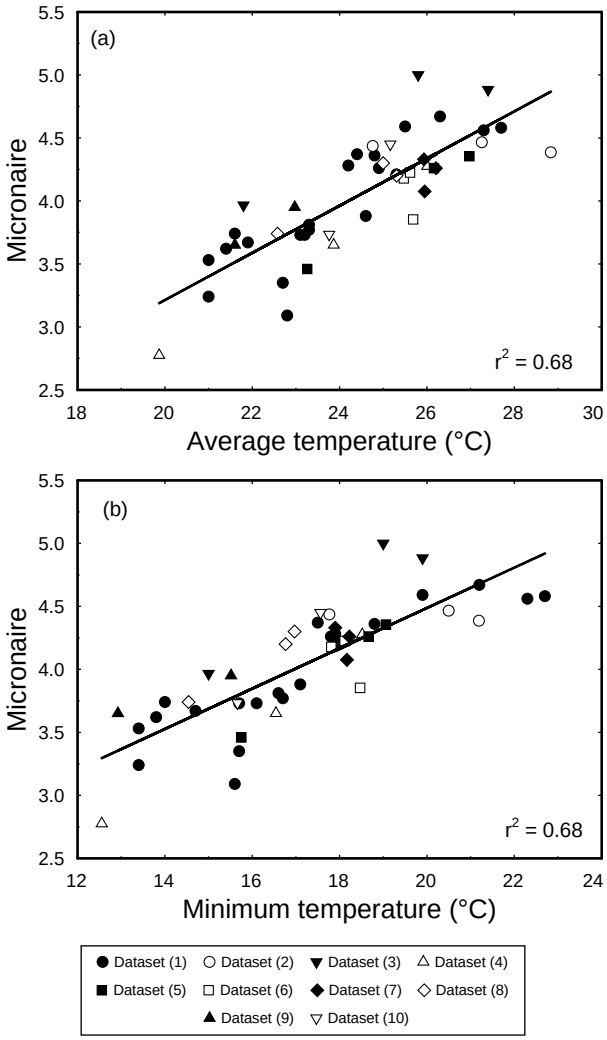

Fig. 1. The response of micronaire measured in sowing time studies to (a) daily average temperature and (b) daily minimum temperature during boll filling. Daily average and minimum temperatures were estimated using the approach proposed in this paper. Datasets are defined in Table 1.

Linear responses of micronaire to temperature have been previously reported (Gipson and Joham, 1968; Gipson and Ray, 1970) along with quadratic responses (Hesketh and Low, 1968; Wanjura and Baker, 1985). Reddy et al. (1999) had a linear increase in micronaire to daily average of 30.3°C and a linear decline after this temperature. In this study no significant decline in micronaire was measured when daily average temperature was 28.8°C and daily minimum was 22.7°C. While Wanjura and Baker (1985) used a quadratic response of micronaire to daily average temperature during boll development, their response showed no substantial decline in micronaire at 26.6°C. Hesketh and Low (1968) and Reddy et al. (1999) measured significant reductions in micronaire at daily average temperatures during boll filling of 33.5 and 32.3°C respectively. In studies on temperature effects on fiber development in cultured ovules Roberts et al. (1992) found no decline in cellulose synthesis with daily temperatures up to 34.0°C.

For micronaire measurements recorded at low temperatures, only studies of Gipson and Joham (1968) (minimum night 8.1°C) and Gipson and Ray (1970) (minimum night 11°C) had lower temperature treatments than those recorded in this study (daily minimum 12.6°C). It is most likely that with more data collected at higher and lower daily average temperatures, the response presented here (Fig. 1) would also be curvilinear.

The degree of change in micronaire with daily minimum temperature in this study (slope 0.16 micronaire units/^{o}C) was greater than measured by Gipson and Joham (1968) using night temperature. For average daily temperature the slope of the response (0.19) was less than that measured by Wanjura and Baker (1985) (slope 0.41 to 0.56) and similar to that of Reddy et al. (1999) (slope 0.21). Variations in these responses are expected as these studies differed in the way developing bolls were exposed to temperature regimes, and how final micronaire values were measured.

This study used daily average and minimum temperatures resulting from changes in sowing time in each experiment, which were applied to micronaire measurements resulting from all bolls harvested from the crop at the end of the season. Controlled environment studies that investigated temperature impacts on micronaire (Gipson and Joham, 1968; Hesketh and Low, 1968; Gipson and Ray, 1970) maintained minimum and maximum temperatures for longer periods throughout the day using square diurnal temperature control. Therefore impacts of higher and lower temperature extremes on micronaire may be greater resulting in temperature responses having lower slopes or being less responsive to temperature changes. In the Wanjura and Baker (1985) study, daily average temperature for individual cultivars were derived from 10 cohorts of bolls tagged over the duration of crop development. It would therefore be expected that a greater range of temperatures would be recorded during boll development and that the range and differences in micronaire would be larger resulting in more sensitive (greater slopes) micronaire versus temperature responses.

Predicting micronaire from temperature. Despite taking no account for other factors that influence micronaire (Constable and Bange, 2007), the methodology that estimated temperature proposed in this study coupled with the micronaire and temperature responses developed (Table 3) were able to predict micronaire well, both on a regionally and temporally diverse dataset (Table 4, Fig. 2) (r^2 0.33 to 0.42). Comparing the ability of daily average and minimum temperature responses to predict micronaire of the CSD data, they were similar in r^2, while the daily average temperature response had less bias across the micronaire predicted (slope closer to unity). The minimum temperature response did however, slightly increase RMSD by 0.08.

Table 4. The regression coefficient (slope), the coefficient of determination (r^2), intercept, and RMSD (root mean square deviation) for predicted versus observed data for micronaire using average daily and minimum temperature for the estimated period of fiber thickening using Cotton Seed Distributor's (CSD) dataset. Table includes analysis of predicted micronaire adjusted for individual cultivar differences. (n = 270).

Analysis	Slope	Intercept	r^2	RMSD
Unadjusted for cultivar				
Average temperature	0.74	1.27	0.34	0.42
Minimum temperature	0.61	1.90	0.33	0.34
Adjusted for cultivar				
Average temperature	0.90	0.79	0.41	0.53
Minimum temperature	0.77	1.32	0.42	0.46

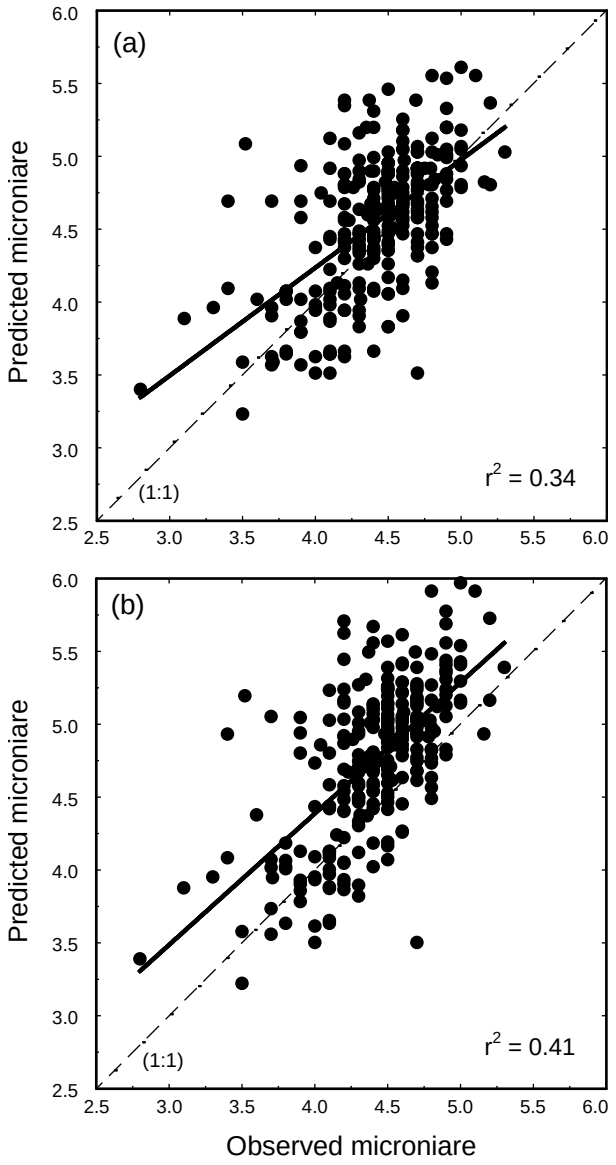

Fig. 2. Predicted micronaire versus observed micronaire for the fiber thickening period using Cotton Seed Distributor's (CSD) dataset: (a) micronaire estimated using the linear response of micronaire to daily average temperature (Table 3) un-adjusted for cultivar differences; (b) micronaire estimated using the same response adjusted for cultivar differences. Solid line is the line of best fit. Dashed line is the 1:1 line. (n = 270).

An adjustment in micronaire prediction to account for inherent cultivar differences reduced the bias and improved r^2 but RMSD was only slightly increased by 0.1 over the unadjusted prediction (Table 4, Fig. 2). This result was not unexpected given the limited range of inherent micronaire (Table 1) of the cultivars used for validation (range 0.12).

Considering the reasonable ability to predict micronaire, we see good opportunities to utilise this approach with confidence to explain or predict the effects of seasonal temperature on micronaire of crops. However, some issues would need consideration before applying this approach more broadly. In addition to extending the temperature range of the micronaire to temperature response mentioned previously, it would include the need for assessing cultivars that have considerably higher and lower inherent micronaire than those used in this study. The inherent micronaire difference of cultivars used was narrow (range 0.55) (Table 1). To improve predictions overall, ongoing research is extending the approach presented here to target the period of micronaire development to capture the combined effects of water stress, changes in boll load, and temperature.

Application of methodology. Utilising historical climate data, this approach has been used in the Australian cotton industry to assess reasons for seasonal and regional differences in micronaire and assess opportunities to improve micronaire with changes in sowing time (e.g. Fig. 3) (Kelly et al., 2006; 2008). These data demonstrate the importance of avoiding low micronaire as a result of late sowing and also indicates the frequency of high micronaire, which needs to be addressed by crop management and by breeding cultivars with lower linear density. This methodology will also be able to predict the whole of seasonal effects on micronaire at the time of harvest aid application and so assist in determining the risks and costs of earlier applications (Wanjura and Newton, 1981). The opportunity also exists to conduct research to predict the components of micronaire (linear density and maturity), which may assist in understanding the impact of climate on fiber quality and resulting textile performance.

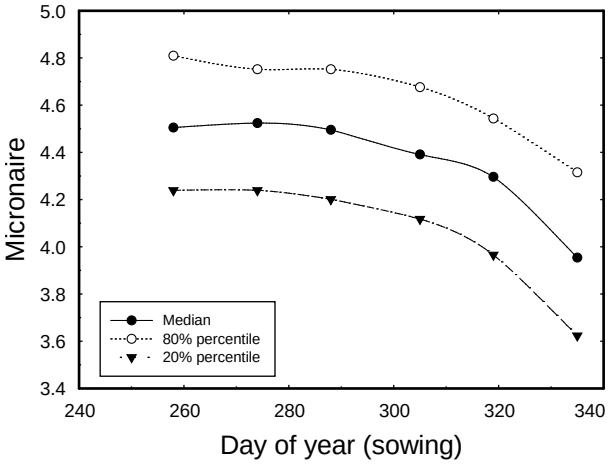

Fig. 3. An example of the use of micronaire predictive capability detailed in this paper to assess the impact on sowing time for Narrabri, NSW, Australia. The micronaire prediction uses the daily average temperature. The median and percentiles are calculated from micronaire predictions for 120 years of temperature data.

CONCLUSION

This study proposed methodology to predict the impacts of temperature on micronaire of cotton crops. This understanding coupled with knowledge of the degree of the effects of radiation, plant defoliation, and competition from bolls for carbohydrate within the plant will improve predictions as well as developing management practices to optimise micronaire.

ACKNOWLEDGMENTS

Thanks to Jane Caton for assistance in the collation of data. Dr Robert Long and Mrs Sandra Williams for helpful discussions about the results. Thanks to Peter Reid, Dr Warwick Stiller, Dr Shiming Liu for provision of multisite data and to Kellie Cooper for fibre quality analyses. The Cotton Research and Development Corporation of Australia and the Cotton Catchment Communities Cooperative Research Centre both provided partial financial support for this work.

REFERENCES

Bange, M.P., S.J. Caton, and S.P. Milroy. 2008. Managing yields of high fruit retention in transgenic cotton (Gossypium hirsutum L.) using sowing date. Aust. J. Agric. Res. 59: 733-741.

Bange, M.P., R.L. Long, G.A. Constable, and S. Gordon. 2010. Minimizing immature fiber and neps in Upland cotton (*Gossypium hirsutum* L.). Agron. J. 102:781-789.

Bange, M.P., E. Brown, J. Caton, and R. Roche. 2004. Sowing time, variety and temperature effects on crop growth and development in the Hillston region. p. 441-447. *In* Proc. 12th Aust. Cotton Conf., Gold Coast, Qld, Aust. 12-14 Aug. 2008. The Aust. Cotton Growers Research Organisation.

Bange, M.P., G.A. Constable, S.G. Gordon, G.R.S. Naylor and M.H.J. Van der Sluijs. 2009. FIBREpak A guide to improving Australian cotton fibre quality. CSIRO and the Cotton Catchment Communities Cooperative Research Centre, Narrabri, Australia.

Bednarz, C.W., D.W. Shurley, and W.S. Anthony. 2002. Losses in yield, quality, and profitability of cotton from improper harvest timing. Agron. J. 94:1004-1011.

Benedict, C.R., R.H. Smith, and R.J. Kohel. 1973. Incorporation of ^{14}C-Photosynthate into developing cotton bolls, *Gossypium hirsutum* L. Crop Sci. 13:88-91.

Brook, K.D., A.B. Hearn, and C.F. Kelly. 1992. Response of cotton, *Gossypium hirsutum* L., to damage by insect pests in Australia: Manual simulation of damage. J. Econ. Entomol. 85:1368-1377.

Constable, G.A. 1991. Mapping the production and survival of fruit on field grown cotton. Agron. J. 83:374-378.

Constable, G.A. and M.P. Bange. 2007. Producing and preserving fiber quality: from the seed to the bale. *In* Proc. 4th World Cotton Conf. Lubbock, USA, 10-14 Sep. 2007.

Constable, G.A., and A.J. Shaw. 1988. Temperature requirements for cotton. Agfact P5.3.5. Division of Plant Industries, New South Wales Department of Agriculture.

Constable, G.A., N.V. Harris, and R.E. Paull. 1976. The effect of planting date on the yield and some fibre properties of cotton in the Namoi Valley. Aust. J. Exp. Agric. Animal Husbandry 16:265-271.

Cousens, R. 1985. An empirical model relating crop yield to weed and crop density and a statistical comparison with other models. J. Agric. Sci. (Cambridge). 105:513-521.

El-Sharkawy, M.A., and J.D. Hesketh. 1964. Effects of temperature and water deficit on leaf photosynthetic rates of different species. Crop Sci. 4:514-518.

Gipson, J.R., and H.E. Joham. 1968. Influence of night temperature on growth and development of cotton (*Gossypium hirisutum* L.). II. Fiber properties. Agron. J. 60:296-298.

Gipson, J.R., and H.E. Joham. 1969. Influence of night temperature on growth and development of cotton (*Gossypium hirisutum* L.). III. Fiber elongation. Crop Sci. 9:127-129.

Gipson, J.R., and L.L. Ray. 1969. Fiber elongation rates in five varieties of cotton (*Gossypium hirisutum* L.) as influenced by night temperature. Crop Sci. 9:339-341.

Gordon, S. and G. Naylor. 2004. Instrumentation for rapid direct measurement of cotton fibre fineness and maturity. *In* Proc. Beltwide Cotton Conf., San Antonio, TX. 5-9 Jan. 2004. Nat. Cotton Council of Am. Memphis, TN.

Jeffrey, S.J., J.O. Carter, K.B. Moodie, and A.R. Beswick. 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environmental Modelling and Software 16:309-330.

Haigler, C.H., N.R. Rao, E.M. Roberts, J.-Y. Huang, D.R. Upchurch, and N.L. Trolinder 1991. Cultured ovules as models for cotton fiber development under low temperatures. Plant Physiology 95:88-96.

Hearn, A.B. 1994. The principles of water relations and their application in management. *In* G.A. Constable and N.W. Forrester, Eds. Proc. The World Cotton Research Conf., Brisbane, Qld, Aust. 14-17 Feb. 1994. CSIRO Australia.

Hearn, A.B., and G.A. Constable. 1984. Cotton. p. 495-527, *In* P.R. Goldsworthy and N.M. Fisher, Eds. The Physiology of Tropical Field Crops. John Wiley and Sons Ltd., Chichester.

Hesketh, J.D., and A. Low. 1968. Effect of temperature on components of yield and fibre quality of cotton varieties of diverse origin. Cotton Grow. Rev. 45:243-257.

Kelly, D., M.P. Bange, and G.A. Constable. 2006. Micronaire and heat in 2005-06. The Australian Cottongrower. 27:8-12.

Kelly, D., M.P. Bange, and G.A. Constable. 2008. Unravelling the micronaire challenge. *In* Proc. 14th Aust. Cotton Conf., Gold Coast, Qld, Aust. 12-14 Aug. 2008. The Aust. Cotton Growers Research Organisation.

Liakatas, A., D. Roussopoulos, and W.J. Whittington. 1998. Controlled-temperature effects on cotton yield and fibre properties. J. Agric. Sci. (Cambridge). 130:463-471.

Lord, E., and S.A. Heap. 1988. The origin and assessment of cotton fibre maturity. Int. Inst. for Cotton, Manchester.

Meinert, M.C., and D.P.Delmer. 1977. Changes in biochemical composition of the cell wall of the cotton fiber during development. Plant Physiol. 59:1088-1097.

Pettigrew, W.T. 1995. Source-to-sink manipulation effects on cotton fiber quality. Agron. J. 87:947-952.

Reddy, K.R., G.H. Davidonis, A.S. Johnson, and B.T. Vinyard. 1999. Temperature regime and carbon dioxide enrichment alter cotton boll development and fiber properties. Agron. J. 91:851-858.

Roberts, E.M., N.R. Rao, J.-Y. Huang, N.L. Trolinder, and C.H. Haigler. 1992 Effects of cycling temperatures on fiber metabolism in cultured cotton ovules. Plant Physiology 100:979-986.

Ryser, U. 1999. Cotton fiber initiation and histodifferentiation. pp 1-45. *In* A.S. Basra ed. Cotton Fibers. Food Products Press, New York.

Schubert, A.M., C.R. Benedict, J.D. Berlin, and R.J. Kohel. 1973. Cotton fiber development - Kinetics of cell elongation and secondary wall thickening. Crop Sci. 13:704-709.

Siebert, J.D., A.M. Stewart. 2006. Correlation of defoliation timing methods to optimize cotton yield, quality, and revenue. J. Cotton Sci. 10:146-154.

Steele, J.D., and J.H. Torrie. 1987. Principals and Procedures of Statistics: a Biometrical Approach. 2nd Edition. McGraw-Hill, Inc. Singapore.

Wanjura, D.F., and G.L. Barker. 1985. Cotton lint yield accumulation rate and quality development. Field Crops Res. 10:205-218.

Wanjura, D.F., and O.H. Newton. 1981. Predicting cotton crop boll development. Agron. J. 723:476–481.

Wanjura, D.F., and J.R. Supak. 1985. Temperature methods for monitoring crop development. p. 369-372. *In* Proc. Beltwide Cotton Prod. Res. Conf., New Orleans, LA. 6-11 Jan. 1985. Natl. Cotton Counc. Am., Memphis, TN.

Wang, Q.C., X.Z. Sun, X.L. Song, Y. Guo, Y. Li, S.Y. Chen, and Wang Z.L. 2006. Effect of shading at different developmental stages of cotton bolls on cotton fibre quality. Acta Agron. Sin. 32:671-675.

Textile Research Journal OnlineFirst, published on September 2, 2009 as doi:10.1177/0040517509343784

Textile Research Journal | Article

Measuring the Maturity of Developing Cotton Fibers using an Automated Polarized Light Microscopy Technique

Robert L. Long[1]
CSIRO Materials Science and Engineering, P.O. Box 21, Belmont, VIC, Australia 3216; Cotton Catchment Communities Cooperative Research Centre

Michael P. Bange
CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW, Australia 2390; Cotton Catchment Communities Cooperative Research Centre

Stuart G. Gordon
CSIRO Materials Science and Engineering, P.O. Box 21, Belmont, VIC, Australia 3216; Cotton Catchment Communities Cooperative Research Centre

Greg A. Constable
CSIRO Plant Industry, Locked Bag 59, Narrabri, NSW, Australia 2390

Abstract Cotton fibers are trichome cells composed primarily of cellulose. Mature fibers have more cellulose and a greater degree of cell wall thickening, and perform better than less mature fibers during textile processing. An automated polarized light microscope instrument called SiroMat that measures cotton fiber cell wall thickening was employed to assess the maturity of developing fibers from single cotton fruit. Fruit were taken from the first fruiting branch and position on glasshouse grown *Gossypium hirsutum* L. (Upland) and *G. barbadense* L. (Pima) plants, sequentially harvested from 24 days postanthesis (dpa) at approximately four-day intervals up until approximately 50 dpa. The instrument assessed an average of 13,000 fiber snippets per fruit. Upland fibers matured at a slower rate than Pima fibers up to 35 dpa. However, after 45 dpa Upland fibers had achieved a higher average maturity (i.e. 0.99 birefringence maturity index (BMI), cf. 0.79 for Pima). For both species the uniformity of fiber maturity increased as fibers matured up until 35 dpa for Upland and 29 dpa for Pima (i.e. the BMI coefficient of variation decreased as BMI increased during fruit development). It is envisaged that SiroMat will be a useful tool in helping to understand and manage fiber maturity by characterizing the maturation dynamics of cultivars with different inherent fiber properties, and for cultivars subjected to different environmental and agronomic conditions.

Key words cotton fiber maturity, cellulose, cell wall thickening, fruit development

Cotton fibers are single-celled trichomes that develop from the epidermis cells on the outer integument of cotton seeds (ovules). Initiation of fiber growth occurs at about anthesis (flowering), following which fiber initials spherically expand above the epidermal surface. Growth of the cotton fiber is continuous and extends for 40 to 60 days postanthesis (dpa) in a series of overlapping phases [1], including a cell elongation phase until 20 to 30 dpa, and a secondary cell wall thickening phase which dominates fiber growth until fruit maturation [2–6]. This secondary cell wall development consists of the deposition of cellulose in a series of

[1] Corresponding author: e-mail robert.long@csiro.au

Figure 2 appears in color online: http://trj.sagepub.com

concentric growth rings or lamellae that reflect circadian rhythms during development [7,8]. Both the elongation and thickening phases are influenced by environmental conditions such as temperature [9] and incident solar radiation [10]. At maturation the cotton fiber remains hollow as a result of the remnant cell protoplasm, which is referred to as the lumen.

Maturity is a term used to describe the degree of cell wall thickening relative to fiber perimeter, which is an important property that affects the textile performance of cotton fibers. Immature fiber, that is fiber with little or no cell wall thickening, is less rigid, making it prone to nep formation during mechanical processing. Neps are unsightly fiber entanglements that diminish the value of both raw cotton and finished cotton products; the flat immature fibers in neps also reflect light differently. In addition, immature fibers do not take up as much dye as mature fibers because the undeveloped cell wall has less cellulose to which dye molecules can bond [11]. As a result dyed yarn and fabric made from immature fiber will appear lighter against yarn and fabric made from more mature fiber.

Understanding the development of the fiber cell wall with respect to plant genotype and environment is therefore important in mitigating these issues. Furthermore, because fibers do not all develop in the same way, considerable dispersion about the mean degree of cell wall thickening is found. Being able to quantify the spread and shape of this dispersion is of value in managing problems associated with fiber consistency. Ideally cotton fibers need to be mature and as uniformly mature as possible. This idea is analogous to HVI fiber length uniformity, which is the ratio of the mean fiber length to the upper-half mean fiber length. Fiber with higher length uniformity is more consistent and is more desirable for textile processing [12,13].

The degree of cell wall thickening, denoted by θ, is quantified as the ratio of the cross-sectional area of the fiber wall (A_w) to the area of a circle with the same perimeter (P) as the fiber cross section (Equation (1)). Figure 1 shows these measurements on immature and mature cotton fiber cross-sections. Although determining θ directly from cross-sections is theoretically the most accurate approach of measuring fiber maturity and is well accepted as such [14–16], the measure suffers from significant experimental error due to the fine detail involved in preparing fibers for measurement and the limited number of fibers that can be practically measured:

$$\theta = 4\pi A_w / P^2 \quad (1)$$

Previous cotton fruit phenology studies have included the measurement of fiber crystallinity [17,18], the biochemical composition of the cell wall [5], the surface chemistry of fibers [19], fiber weight per seed and fiber length [3,4,20]. Such reports typically examined both common commercial Upland cotton (*Gossypium hirsutum* L.) and the less common and lower yielding but premium quality Pima-type cotton (*G. barbadense* L.). Few reports have measured the development of cotton cell wall thickening. Seagull et al. [21] reported changes in fiber diameter and relative birefringency from 5 to 50 dpa, although there was no measure specifically of relative fiber maturity. Bradow et al. [22] employed the Uster Technologies Advanced Fiber Information System (AFIS) to measure fiber maturity properties (cross-sectional area and circularity) for developing Upland and Pima fruit from 21 to 56 dpa. They reported comparisons between AFIS maturity and fiber "physiochemical maturity" as determined with calcium x-ray fluorescence spectroscopy.

Currently the only routine methods of determining cotton fiber maturity are via instruments such as the "Fineness and Maturity Tester" (FMT) instruments (e.g. as originally produced by the Shirley Institute), and via the

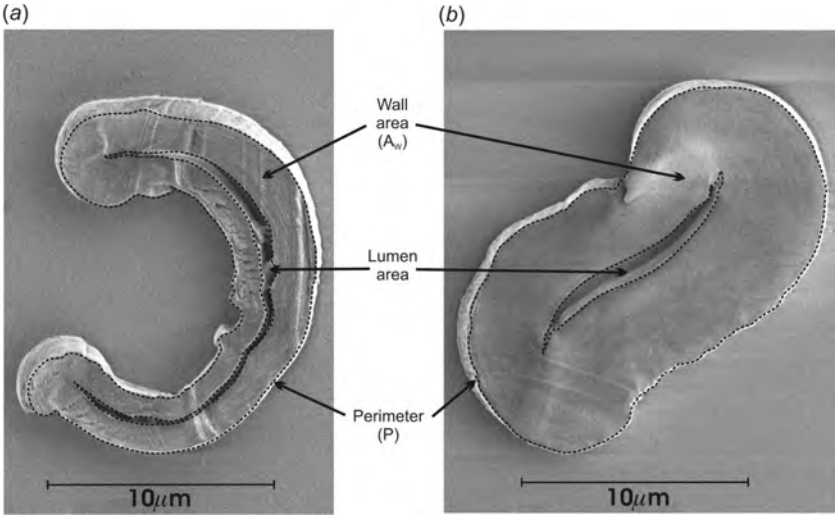

Figure 1 Cross-sections of (*a*) immature and (*b*) mature cotton fibers showing the measurements required to calculate the degree of cell wall thickening.

AFIS instrument. FMT instruments measure air-flow through a 4 g plug of fibers at two compressions, giving an average reading of maturity for a given sample. The AFIS instrument requires a 0.5 g sample prepared into a 25 cm-long sliver, and the maturity test is based on measuring an electro-optical signal as individualized fibers are conveyed by air through a light beam. Data for individual fibers or fiber segments are collected, and in addition to an average fiber maturity result, the AFIS also provides a measurement called the Immature Fiber Fraction, which attempts to quantify the fraction of immature fiber with a θ value less than 0.25. Both technologies require the sample to be temperature and humidity-conditioned prior to testing.

This study employs another approach to measuring cotton fiber maturity via the SiroMat instrument, a polarized light microscope-based technology recently developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) [23]. SiroMat measures the maturity for several tens of thousands of cotton fiber snippets from a (smaller) sample of approximately 5 mg. In so doing the instrument quantifies a frequency distribution of a sample, thus not only giving an average maturity reading, but also detailing the variability or dispersion statistics of the distribution. The aim of this work was to investigate the maturity of cotton fibers from individual fruit of different developmental ages for an Upland cultivar and a Pima cultivar. It is envisaged that SiroMat will be a useful tool in helping to characterize the maturity dynamics of cultivars with different fiber properties, and for cultivars subjected to varying environmental and production conditions, with the intention of maximizing fiber maturity as well as improving the consistency of fiber maturity.

Materials and Methods

Measuring Fiber Maturity – SiroMat Instrument

The SiroMat is based on polarized light microscopy, a technique that has long been used to investigate fibers that exhibit birefringent properties, i.e. fibers that behave like uni-axial optical crystals. The optical axis in birefringent fibers is usually parallel to the fiber axis with the refractive index being dependent upon the plane of polarization of the incident light. When plane-polarized light is transmitted through a birefringent object, the light ray is split into two mutually perpendicular vibrating fast and slow rays, which propagate through the object at two different speeds. Upon emerging from the object, a phase difference occurs between the fast and slow rays. When recombined into a single ray by passage through a second polarizer (analyzer) the rays interfere with each other, which in turn creates different interference colors that highlight the crystalline oriented aspects of the specimen [24].

The interference colors assumed by cotton fibers under crossed polars are the result of the optical phenomena described above and have been related to measures of relative fiber maturity by Schwarz and Hotte [25] and Grimes [26]. The disadvantage of the test, however, is that the operator must make an arbitrary assessment of the colors assumed by the fibers. It is this subjective decision by the operator that contributes to large discrepancies in the results from different laboratories. The ASTM Standard Test Method for Maturity of Cotton Fibers (Sodium Hydroxide Swelling and Polarized Light Procedures) [27] for measuring fiber maturity by polarized light microscopy in fact warns against using the method for acceptance testing because of poor precision. Furthermore, the test is too slow for routine test applications, both in terms of specimen preparation and test time.

SiroMat overcomes these issues by using a color CCD camera, an automated XY microscope stage and image analysis software to automatically scan, digitize and analyze fibers on the basis of their interference colors. The automation means that the selection of fibers and interpretation of their color is no longer subject to operator interpretation [23].

The maturity of fibers viewed under polarized light microscopy is indicated by their yellow and green color [25–27]. Previous work presented by Gordon and Phair [23] showed the percent yellow area of fibers measured under a prototype SiroMat was significantly more related to the θ value of cotton fibers than to absolute cross-sectional wall area or wall thickness.

Figure 2 shows a typical field-of-view (fov) analyzed by SiroMat. SiroMat automatically captures and analyzes cotton fiber snippet images in 36 fov; each fov measures 3.46 mm × 2.60 mm. The percent area color measurement is determined using a series of standard image analysis

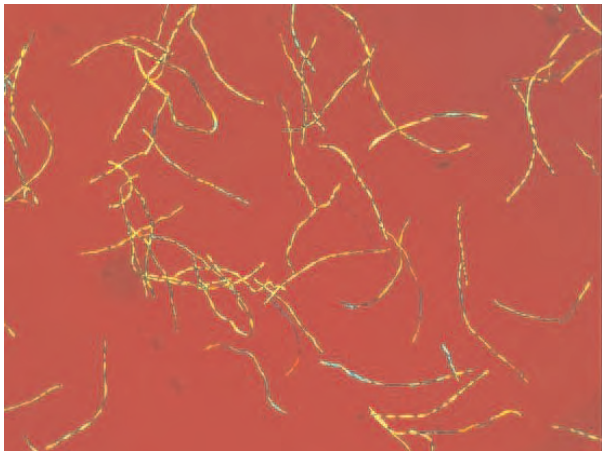

Figure 2 SiroMat field of view (3.46 × 2.60 mm^2) of cotton fibers of normal maturity. Thirty-six field of view images are acquired and compiled per instrument replicate.

functions starting with edge detection to find the boundaries of fibers, followed by image dilation to join small disconnected pieces (pixels) together. The image is then converted to a binary image based on a grey-scale threshold, and the resultant image is used as a mask to select the fiber area from the background.

Following creation of the mask the image is broken up into fiber sections according to image cross-over points. To do this the mask image is skeletonized to reveal branch points, which are used to segregate and label fiber sections. The image at this point is a mask with a number of labeled segments, each segment containing a portion of a single fiber snippet. A background correction and normalization is applied to the original color image before the proportion of pixels in each color threshold bin, i.e. yellow, red, green and blue, is counted for each segment in the mask. Color threshold levels are set according to a digital color space model, which defines changes in hue according to numerical segments between the values of 0 and 255. A multiple linear regression equation (Equation (2)) is used to convert the percent area of yellow and green colors in the fiber snippet images to their respective fiber maturity values (termed the birefringence maturity index (BMI)).

Maturity ratio as described by Peirce and Lord [28] and used in the ASTM Standard Test Method for Maturity of Cotton Fibers [27], is a widely used fiber maturity scale. The ratio is linearly related to θ according to Equation (3). Fiber BMI for the version of SiroMat used in this study is scaled using FMT maturity ratio values measured on a set of 56 international and Australian cottons (mean maturity ratio = 0.78, SD = 0.07); the linear relationship between actual FMT maturity ratio values and predicted BMI values via SiroMat (Equation (2)) is significant ($R^2 = 0.74$, $P < 0.001$). Work on the development of a conversion equation using the 104 International Textile Center maturity reference cottons [16] is continuing:

$$\text{BMI} = 2.454Y - 1.078G - 0.332 \quad (2)$$

$$\text{Maturity ratio} = \theta/0.577 \quad (3)$$

where Y and G are the proportional areas of yellow and green respectively in the fiber snippet image(s) captured by SiroMat.

As well as calculating an average maturity result, the SiroMat instrument also gives the related dispersion statistics (i.e. standard deviation, skew and a frequency histogram of BMI) for each sample. The benefits of using SiroMat in this application relate to the ease of preparing and measuring small (circa 5 mg) specimens of fiber such as small amounts of hand-ginned material from single fruit. Another advantage is that the specimen does not need to be dried or conditioned for a weight-based measurement, as is required, for example, for air-flow (FMT) measurements of fiber maturity.

Glasshouse Experiment

G. hirsutum L. (Sicot 71BR, CSIRO Australia) and *G. barbadense* L. (Sipima 280, CSIRO Australia) plants were grown in a glasshouse located at the Australian Cotton Research Institute at Narrabri (30.3°S, 149.8°E). Seeds were sown at 30 mm depth into 9 L, 250 mm diameter, draining pots containing grey-clay soil (vertosol). One plant was grown per pot, with pots randomly positioned to ensure that both species were grown under similar conditions. Irrigation was via a dripper system which delivered 150 mL twice a day to each pot. Mineral nutrition was via an all-purpose fertilizer (NPK, 15.0 : 13.1 : 12.4 plus trace elements) delivered every two weeks at a rate of 1.25 mL/L to ensure non-limiting conditions.

The first-position flowers on the first flowering branch were tagged at anthesis. Fruit harvest commenced at 7 dpa, and continued at approximately four-day intervals until fruit were mature and the carpels were starting to open. Three fruit (from three plants) were collected per time treatment; of these, one fruit was randomly selected for fiber maturity analysis. Although plants that had fruit removed were no longer used in the experiment they remained in position to limit differences in effects between plants. Following harvest all fruit were frozen (at –3 to –5°C) for storage.

Measuring Fiber Maturity using SiroMat

Fruit selected for maturity testing were defrosted at ambient laboratory conditions. Fruit were opened with a razor blade and the seeds and fibers were separated from the carpels. Four or five seeds were randomly selected from the center of each fruit for fiber analysis. Fibers in young fruit were packed tightly together and bound by a mucilaginous matrix when they dried out. To break down this matrix and to help individualize fibers, the seeds and lint were boiled for 2 min in 1M HCl, and then immersed in ambient reverse osmosis water for approximately 1 min to wash and cool material, as adapted from [21]. Seeds with fibers attached were drained and stored in plastic Petri dishes and refrigerated at 4°C until SiroMat analysis.

Dried fiber specimens (still attached to the seed) were gently combed using combs from a 'Shirley' Comb Sorter to align and separate fibers before cutting. Fibers on less mature ovules were aligned whilst still wet and then further combed when dried. Combed fibers still attached to the seed were cut at their mid-section using a purpose built guillotine with a blade width of 1 mm.

Collected fiber snippets were spread in an annular pattern on 50 mm × 70 mm glass slides using an OFDA™ fiber spreader (BSC Electronics). A clean 50 × 70 mm^2 slide was used to cover the specimen. Castor oil (refractive index = 1.477 – 1.481) was used as the mounting medium to enhance the contrast of the fiber snippets to their background. Preparing the SiroMat instrument involved adjust-

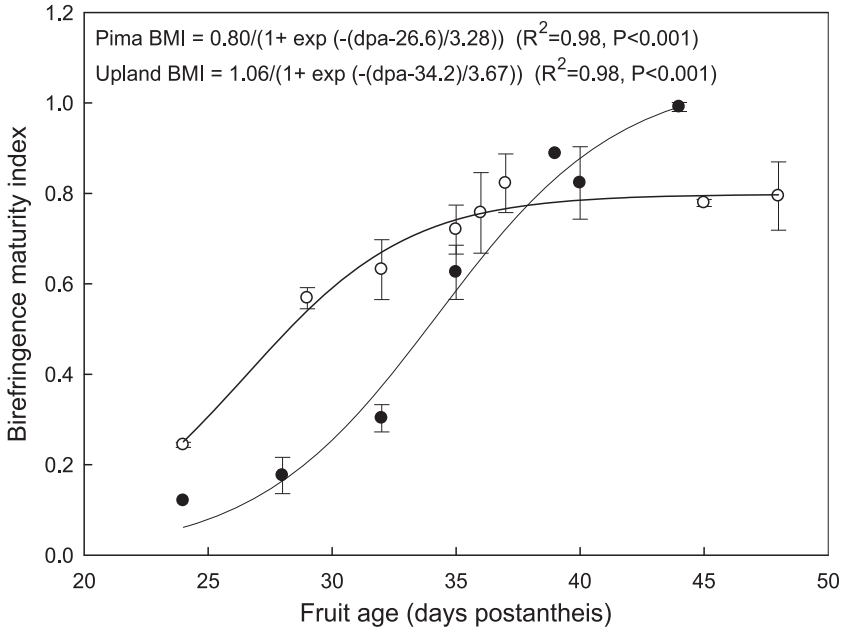

Figure 3 Cotton fiber birefringence maturity index for first position fruit from glasshouse grown Upland (●) and Pima (○) plants. Values are mean ± standard deviation of two SiroMat measurements taken on each fruit.

ing the digital camera settings (U balance, V balance and shutter speed) and the microscope lamp intensity to match a prescribed background (magenta) color in terms of red, green and blue ratios. Background colors were also checked at regular intervals during testing to minimize drift in the color temperature of the microscope lamp. Two slides were prepared and tested per fruit. Samples from fruit younger than 24 dpa were not suitable for SiroMat analysis because fibers from these samples were still bound together.

Curve Fitting

The relationship between BMI and fruit age (dpa) was quantified by a three parameter sigmoidal model generated using Sigma Plot 10:

$$Y = a/(1 + \exp(-(X - x_0)/b)) \quad (4)$$

where Y is BMI and X is fruit age (dpa).

Results and Discussion

Fiber Preparation

The method of fiber extraction inadequately prepared fibers from fruit younger than 24 dpa. Although the fibers were boiled for a short time to aid in dissolving the mucilaginous matrix (or matrix polysaccharides, recently described as the cotton fiber middle lamella [29]), our method was insufficient and fibers could not be singled out at this young stage. Seagull et al. [21] succeeded in individualizing fibers as early as 5 dpa, but the number of fibers they assessed was small (circa 50); it is assumed that considerable manual individualization following their boiling treatment would have been practical for this small number. In our case an average of approximately 13,000 fiber snippets were assessed per fruit, ruling out any manual manipulation of bound or semi-bound fibers. Indeed, other published work reporting single fiber measurements did not report data for fibers younger than about 15 to 20 dpa [14,22,30], presumably because of the challenge in individualizing fibers from younger fruit.

Fiber Maturity Development

For both the Upland cultivar and the Pima cultivar, cell wall development curves were explained by sigmoidal functions (Figure 3), although it is acknowledged that being able to measure the BMI for fibers from fruit younger than 24 dpa may have allowed a stronger "S" shape to have been characterized, particularly for Pima. Nevertheless, sigmoidal curves were expected and were in harmony with other cotton fruit developmental work characterizing parameters indexing fiber maturity such as fiber weight per length [3] and the amount of cellulose per fiber length [5].

The progression in BMI for the two cotton cultivars over the measurement period was different. The Pima cultivar fibers appeared to mature more quickly, with fiber BMI reaching a plateau at about 37 dpa; the Upland cultivar fibers continued to mature until 45 dpa (Figure 3). Although Pima matured earlier, Upland fibers were ulti-

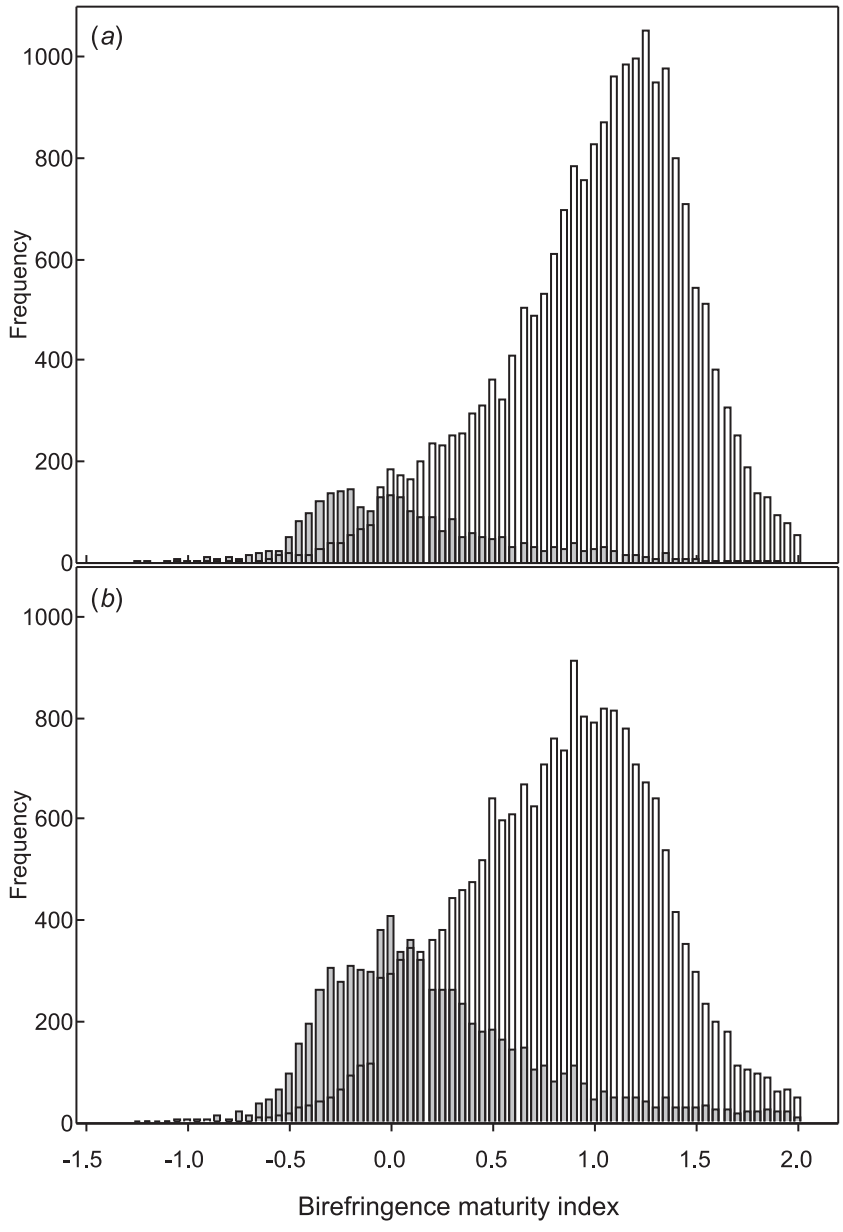

Figure 4 Frequency histogram of cotton birefringence maturity index for (*a*) Upland fruit harvested at 24 dpa (grey box) and 44 dpa (open box), and for (*b*) Pima fruit harvested at 24 dpa (grey box) and 48 dpa (open box).

mately more mature, i.e. Upland fibers at 44 dpa had a BMI of 0.99 whilst Pima fibers at 48 dpa had a BMI of 0.79 (Figure 3). Seagull et al. [21] reported a similar trend, and showed that the birefringence of developing Pima fibers plateaued earlier compared with Upland fibers; at full maturity two of the three Upland cultivars assessed displayed higher birefringence values than Pima. It is conceded that these differences may well be related to cultivar and are not a definitive explanation of the general fiber maturity dynamics for *G. hirsutum* L. and *G. barbadense* L. species. Indeed, work by Bradow et al. [22] showed no distinct differences in the shape of development curves of fiber maturity (circularity, θ) for developing Upland and Pima fruit, although their work did show that Upland fibers were more mature than Pima fibers. A higher maturity in Upland compared with Pima presents an opportunity to potentially improve the maturity of Pima cotton.

Fiber Maturity Dispersion

The distribution of fiber maturity for the earliest and latest harvested fruit for both species is displayed in Figure 4. The range of BMI values in these plots reflects the regression Equation (2) algorithm used to convert the proportion

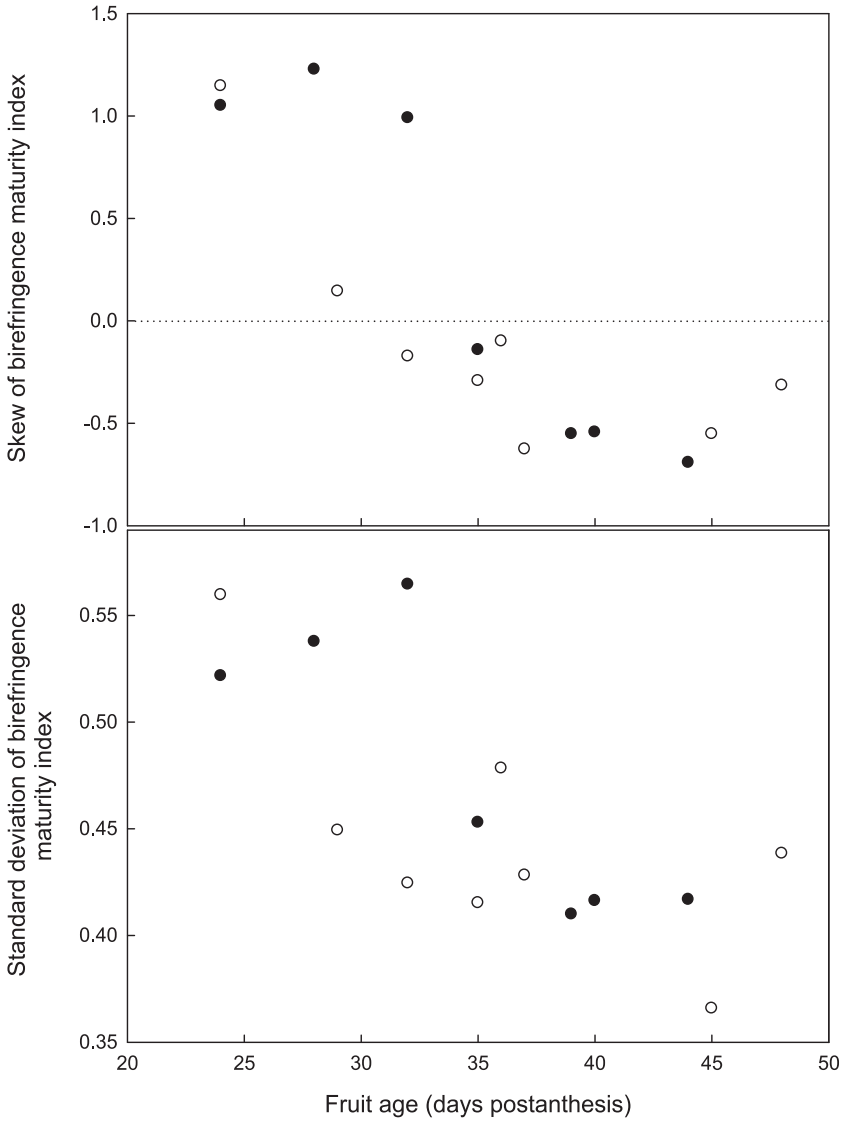

Figure 5 Skew and standard deviation of cotton fiber birefringence maturity index of first position fruit from glasshouse grown Upland (●) and Pima (○) plants. Data common to Figure 2.

of yellow and green colors into BMI values. According to this equation a range of BMI values from –1.4 to 2.1 is possible, e.g. when $Y = 0$ and $G = 1$ or $Y = 1$ and $G = 0$, although exclusion of measurements with 0 and very small color areas means the calculated range is reduced to a range between –1.2 and 2.0. The theoretical range of maturity ratio values is from 0.2 to 1.2; however, as already noted, it is difficult to measure maturity on very immature fiber specimens, so the actual range may not have been fully revealed in previous studies. It is intended that future calibrations for SiroMat will ensure that BMI better represents maturity ratio.

Figure 5 summarizes the dispersion measured as the standard deviation and skew of the maturity distribution for each cotton sample. These values are common to the average BMI values plotted in Figure 3. As fiber for both species increased in maturity, the skew of BMI became negative, and the standard deviation of BMI decreased (Figure 5). This negative relationship between average maturity and these two measures of dispersion has been found in other SiroMat sample sets tested to date [31,32]. There were no distinct differences between the two cultivars for trends of these dispersion statistics during fruit development. However, in order to compare the amount of error associated with the changing mean BMI values, a coefficient of variation was calculated to provide clearer information about the uniformity or consistency of maturity for each sample:

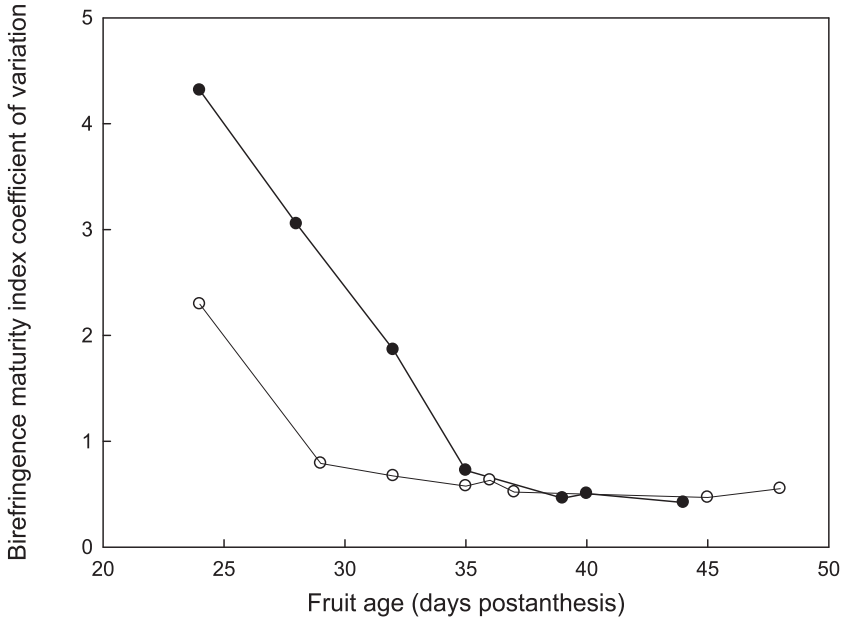

Figure 6 Birefringence maturity index coefficient of variation of first-position fruit from glasshouse grown Upland (●) and Pima (○) plants.

$$\text{BMI coefficient of variation} = \text{standard deviation of BMI/mean BMI} \quad (5)$$

Pima fibers were more uniform in younger fruit and reached a plateau below 1 BMI coefficient of variation unit at about 29 dpa (Figure 6). Both Upland and Pima fibers had similar maturity uniformity by 35 dpa, and although Upland fibers continued to mature the uniformity of fiber maturity did not appear to markedly improve (Figure 6).

Fiber that has a narrower, more uniform distribution is more consistent and desirable for textile processing. The SiroMat instrument could be used at the breeding level to evaluate lines of interest to screen for high maturity and maturity uniformity. Likewise, in developing management strategies to optimize fiber quality SiroMat information would assist with the detailed assessment of results of different treatments. It would be of interest to compare the textile performance of fiber with similar maturity but with a range of maturity distributions.

Conclusion

The SiroMat polarized light microscope was employed to measure the maturity of fibers from developing Upland and Pima cotton fruit, with the intention of demonstrating the future usefulness of the instrument. SiroMat was able to assess an average of 13,000 fiber snippets per fruit (circa 5 mg sample) from 24 dpa. Pima fibers matured more quickly than Upland fibers, but Upland fibers ultimately achieved a higher average maturity. For both species the uniformity of fiber maturity increased as fibers matured, although a distinct change in the rate of increase in maturity uniformity was noted (at 35 dpa for Upland, and at 29 dpa for Pima). Further research assessing a greater number of Upland and Pima cultivars is required to confirm differences between these two species. It is envisaged that SiroMat will be a useful tool in helping to understand and manage fiber maturity by characterizing the maturation dynamics of cultivars with different inherent fiber properties, and for cultivars subjected to different environmental and agronomic conditions.

Acknowledgements

The authors thank the Cotton Research and Development Corporation, the Cotton Catchment Communities Cooperative Research Centre and the CSIRO for financial support. Much gratitude goes to Rose Brodrick, Darin Hodgson, Erica Cuell, Jane Caton, Karen Letts and Nicole Phair-Sorensen for their excellent technical support. We also thank Margaret Pate and Bea Lipson for fiber cross sectioning and electron microscopy work.

Literature Cited

1. Wilkins, T. A., and Jernstedt, J. A., Molecular Genetics of Developing Cotton Fibers, in "Cotton Fibers, Developmental Biology, Quality Improvement, and Textile Processing," Basra, A. (ed), Food Products Press, Binghampton, NY, 1999, pp. 231–269.

2. Benedict, C. R., Smith, R. H., and Kohel, R. J., Incorporation of ^{14}C-phoyosynthate into developing cotton bolls *Gossypium hirsutum L.*, *Crop Sci.* **13**, 88–91 (1973).
3. Schubert, A. M., Benedict, C. R., Berlin, J. D., and Kohel, R. J., Cotton fiber development kinetics of cell elongation and secondary wall thickening, *Crop Sci.* **13**, 704–709 (1973).
4. Kohel, R. J., Quinsberry, J. E., and Benedict, C. R., Fiber elongation and dry weight changes in mutant lines of cotton, *Crop Sci.* **14**, 471–474, (1974).
5. Meinert, M. C., and Delmer, D. P., Changes in biochemical composition of the cell wall of cotton fiber during development, *Plant Physiol.* **59**, 1097–1099 (1977).
6. Ryser, U., Cotton Fiber Initiation and Histodifferentiation, in "Cotton Fibers, Developmental Biology, Quality Improvement, and Textile Processing," Basra, A. (ed), Food Products Press, Binghampton, NY, 1999, pp. 1–45.
7. Kerr, T., The structure of the growth rings in the secondary wall of the cotton hair, *Protoplasma*, Verlag von Gebriider Borntraeger, Leipzig, 1937, pp. 229–241.
8. Maxwell J. M., Gordon, S. G., and Huson, M. G., Internal structure of mature and immature cotton fibers revealed by scanning probe microscopy, *Textile Res J.* **73**, 1005–1012 (2003).
9. Gipson, J. R., and Ray, L. L., Fiber elongation rates in five varieties of cotton (*Gossypium hirsutum* L.) as influenced by night temperature, *Crop Sci.* **9**, 339–341 (1969).
10. Wang, Q., Sun, X., Song, X., Guo, Y. Li, Y., Chen, S. Y., and Wang, Z., Effect of shading at different stages of cotton bolls on cotton fiber quality. *Acta Agronomica Sinica* 32, 671–675 (2006).
11. Van der Sluijs, M. H. J., and Hunter, L., Neps in cotton lint, *Textil. Progr.* **28**, 1–51 (1999).
12. Behery, H.M., "Short Fiber Content and Uniformity Index in Cotton," CAB International, Wallingford, Oxon, 1993.
13. Anthony, W.S., and Mayfield, W.D., "Cotton Ginners Handbook – Agricultural Handbook number 503," United States Department of Agriculture, Washington, DC, 1994.
14. Lord, E., and Heap, S. A., "The Origin and Assessment of Cotton Fiber Maturity," International Institute for Cotton, Manchester, 1988.
15. Thibodeaux, D. P., and Rajasekaran, K., Development of new reference standards for cotton fiber maturity, *J. Cotton Sci.* **3**, 188–193 (1999).
16. Hequet, E. F., Wyatt, B., Abidi, N., and Thibodeaux, D. P., Creation of a set of reference material for cotton fiber maturity measurements, *Textile Res. J.* **76**, 576–586, (2006).
17. Nawar, M. T., Khalifa, B. A., and Al-Ganainy, G., Crystallinity, crystallite size, fine structural and physical fiber properties at two fiber maturity levels in two Egyptian cotton cultivars, in "Proceedings of the 1st World Cotton Research Conference", Brisbane Australia, 1994, pp. 258–263.
18. Hsieh, Y-L, Chemical structure and properties of cotton, in "Cotton: Science and Technology", Gordon, S., and Hsieh, Y-L. (eds), Woodhead Publishing Limited, Cambridge, England, 2007, pp. 3–34.
19. Gamble, G., Variation in surface chemistry constituents of cotton (*Gossypium hirsutum*) fiber as a function of maturity, *J. Agric. Food Chem*, **51**, 7995–7998 (2003).
20. Schubert, A. M., Benedict, C. R., Gates, C. E., and Kohel, R. J., Growth and development of the lint fibers of Pima S-4 cotton, *Crop Sci.* **16**, 539–543 (1976).
21. Seagull, R. W., Oliveri, V., Murphy, K., Binder, A., and Kothari, S., Cotton fiber growth and development. 2. Changes in cell diameter and wall birefringence, *J. Cotton Sci.* **4**, 97–104 (2000).
22. Bradow, J. M., Hinojosa, O., Wartelle, L.H., Davidonis, G., Sassenrath-Cole, G.F., and Bauer, P.J., Applications of AFIS fineness and maturity module and x-ray fluorescence spectroscopy in fiber maturity evaluation, *Textile Res. J.* **66**, 545–554 (1996).
23. Gordon, S. G., and Phair, N. L. P., An investigation of the interference colors in mature and immature cotton fibers, in "Proceedings of the Beltwide Cotton Conferences", National Cotton Council, New Orleans LA, 2005.
24. Hecht, E., "Optics", 2nd edn, Addison-Wesley, Reading, Massachusetts, 1987.
25. Schwarz, E. R., and Hotte, G. H., Micro-determination of cotton fiber maturity in polarized light, *Textile Res. J.* **5**(8), 370–376 (1935).
26. Grimes, M. A., Polarized Light: Preferred for Maturity Tests, *Textile World*, 161–163, February (1945).
27. American Society for Testing and Materials Designation: D1442-00, 'Standard Test Method for Maturity of Cotton Fibers (Sodium Hydroxide Swelling and Polarized Light Procedures)', 2000, pp. 354–359.
28. Peirce, F. T., and Lord, E., The fineness and maturity of cotton, *J. Textile Inst.* **30**, T173–T210, (1939).
29. Singh, B., Avci, U., Eichler Inwood, S. E., Grimson, M. J., Landgraf, J., Mohnen, D., Sorensen, I., Wilkerson, C. G., Willats, W. G. T., and Haigler, C. H., A specialized outer layer of the primary cell wall joins elongating cotton fibers into tissue-like bundles, *Plant Physiol*. **150**, 684–699 2009.
30. Hsieh, Y-L, Structural development of cotton fibers and linkages to fiber quality, in "Cotton Fibers, Developmental Biology, Quality Improvement, and Textile Processing," Basra, A. (ed), Food Products Press, Binghampton, NY, 1999, pp. 137–165.
31. Gordon, S. G., Long, R. L., Bange, M., Lucas, S. R., and Phair-Sorensen, N. L., Measurement of average maturity and maturity distribution statistics by SiroMat in cotton fiber subject to differential defoliation timing treatments, in "Proceedings of the Beltwide Cotton Conferences", National Cotton Council, New Orleans LA, 2007.
32. Gordon, S. G., Long, R. L., Lucas, S. R., and Phair-Sorensen, N. L., Using SiroMat to distinguish fiber maturity related issues in the mill, in "Proceedings of the Beltwide Cotton Conferences", National Cotton Council, Nashville TN, 2008.

Field Crops Research 121 (2011) 401–407

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Consequences of immature fiber on the processing performance of Upland cotton

Robert L. Long[a,c,*], Michael P. Bange[b,c]

[a] CSIRO Materials Science and Engineering, P.O. Box 21, Belmont, Victoria 3216, Australia
[b] CSIRO Plant Industry, Locked Bag 59, Narrabri, New South Wales 2390, Australia
[c] Cotton Catchment Communities Co-operative Research Center, Australia

ARTICLE INFO

Article history:
Received 28 September 2010
Received in revised form
20 December 2010
Accepted 15 January 2011

Keywords:
Cotton fiber maturity
Fineness
Cotton dyeing
Ribbon width
Fiber diameter
Yarn strength

ABSTRACT

Immature cotton fiber will negatively impact textile processing. Three field experiments were undertaken that applied chemical harvest aids to upland cotton (*Gossypium hirsutum* L.) crops at varying times with the intention of manipulating the maturity of bolls and fibers. The aim was to quantify the effects of these treatments on the textile performance of the harvested cotton and relate these differences to the status of the crop at the time of treatment application. Although earlier treatments produced less mature fiber that was lower in linear density, yarn and fabric strength was not affected. However less mature cotton from a cooler growing season produced stronger yarns (by 3 cN tex^{-1}) and fabric (by 0.39 N (g m^{-2})$^{-1}$) which was partly attributed to the smaller ribbon width of this fiber affecting more fiber packing density and inter-fiber friction. Yarns made from this immature cotton also contained more neps. Micronaire and linear density were equally well related, and more strongly related than maturity ratio, to dyed fabric color dimensions, which were greatly influenced by treatments. Percent immature bolls at the time of harvest aid application related well to changes in the degree of fabric blueness (R^2 = 0.89). Knowing the status of a crop in the final stages of production will help cotton producers and the supply chain to predict some of the processing performance aspects of harvested fiber.

1. Introduction

Cotton fiber development consists of a number of distinct phases including the deposition of cellulose in the secondary cell wall. This degree of cell wall thickening is referred to as fiber maturity, with mature fibers having more thickening so that the hollow space in the fiber, the lumen, is small. Immature fibers have less cell wall thickening with a larger lumen and are undesirable because they reflect light differently and do not uptake dye as effectively as mature fibers and will appear a lighter hue (Smith, 1991). Immature fiber will also entangle more easily and form neps (knots) which contribute to processing inefficiencies and appear as 'white specks' or flecks on finished fabric. Delays in boll and fiber maturity are caused by less than optimal crop growing conditions including cold temperatures (Liakatas et al., 1998), excessive nutrition (Cassman et al., 1990) and other crop management decisions (Roberts and Constable, 2003) including the early application of harvest aids (Snipes and Baskin, 1994).

Fiber maturity will influence the fineness of fibers. 'Fineness' refers to two interrelated conditions, firstly as a term for fiber weight per unit length or linear density, and secondly it pertains to fiber diameter or ribbon width. Typically fibers with smaller diameters will be lower in linear density and therefore are regarded as finer. Fineness contributes to yarn strength because stronger yarns contain either more finer fibers (smaller diameter or width) in a given volume resulting in greater packing density and inter-fiber friction, or there will be a greater total number of fibers of lower linear density in the yarn cross section (Goswami et al., 1977; Sullivan, 1942). While fiber maturity will affect linear density, maturity also has potential to additionally affect fiber fineness or coarseness because the degree of cell wall thickening may influence the external dimensions of fibers. For example a flatter immature collapsed fiber may have a smaller ribbon width compared to a fuller more mature fiber.

This paper details findings extending on from those reported by Bange et al. (2010) in which the timing of harvest aids were systematically varied on maturing cotton crops to influence the proportion of immature fiber and neps in the crop. These quality attributes were related to different measures of crop status at the time of treatment application, and recommendations for refining management strategies for harvest aid timing were suggested to optimize yield and quality. The work herein reports on the effects of the same experimental treatments but with emphasis on the processing performance of the treated cotton fiber. The aim of this work includes ascertaining which plant status and fiber quality measures best reflect changes in yarn and fabric performance, as well as quantifying the effects of harvest aid timing on these textile attributes.

* Corresponding author at: CSIRO Materials Science and Engineering, P.O. Box 21, Belmont, Victoria 3216, Australia. Tel.: +61 3 5246 4000; fax: +61 3 5246 4057.
E-mail address: robert.long@csiro.au (R.L. Long).

0378-4290/$ – see front matter.
doi:10.1016/j.fcr.2011.01.008

Table 1
Impact of harvest aid timing treatments on fiber quality attributes micronaire, maturity ratio, linear density and ribbon width, for all experiments.

Harvest aid treatment	% immature bolls	Micronaire	Maturity ratio	Linear density mtex	Ribbon width μm
Exp. 1					
1	67.5	4.1	0.88	172	14.8
2	41.0	4.2	0.91	181	14.8
3	23.4	4.6	0.98	194	14.9
4	22.2	4.6	0.91	191	15.0
5	21.1	4.3	0.95	183	14.8
6	12.5	4.7	0.91	195	15.0
7	6.1	4.6	0.95	196	15.1
8	0.0	4.6	0.95	193	15.0
Average		4.4	0.93	188	14.9
LSD (0.05)		0.4*	0.10	12**	0.2
Exp. 2					
1	64.9	4.2	0.82	179	14.7
2	56.6	4.6	0.85	188	14.7
3	50.1	4.7	0.90	196	14.9
4	36.1	4.9	0.95	202	14.9
5	19.8	5.2	0.91	207	15.1
6	10.2	5.1	0.95	205	14.9
7	10.1	5.0	0.99	210	15.0
8	0.0	4.9	0.90	201	14.9
Average		4.8	0.91	198	14.9
LSD (0.05)		0.4***	0.10*	11***	0.3
Exp. 3					
1	88.2	3.0	0.53	159	14.6
2	81.0	2.9	0.69	152	14.7
3	72.4	3.3	0.63	173	14.8
4	72.2	3.6	0.65	178	14.7
5	40.4	3.7	0.75	182	14.8
6	20.0	3.8	0.75	191	14.7
Average		3.4	0.67	172	14.7
LSD (0.05)		0.3***	0.15*	9***	0.2
LSD (0.05) Exps.		0.4***	0.06***	12**	0.1*

* ANOVA was significant at the 0.05 level.
** ANOVA was significant at the 0.01 level.
*** ANOVA was significant at the 0.001 level.

The hypothesis that fiber maturity affects fiber fineness and thus yarn strength is also briefly examined.

2. Materials and methods

2.1. Cultural details, treatments, and measures of plant status and fiber quality

Full experimental details are described in Bange et al. (2010). Briefly, field experiments were conducted at the Australian Cotton Research Institute at Narrabri, NSW, Australia (30°S 150°E) in which a single mixture of harvest aids, designed to cause leaf shed and to increase the rate of boll opening, was applied to cotton crops with different proportions of open bolls. Experiments were conducted in the 2006, 2007 and 2008 harvest seasons, designated as experiment (Exp.) 1, 2 and 3, respectively. Treatments were an application of a mixture of leaf defoliant and a boll opener; being Dropp Liquid® (Bayer CropScience), Prep 720® (Bayer CropScience) and D-C Tron® (Caltex) applied at approximately 5 d intervals in Exps. 1 and 2, and at 7 d intervals in Exp. 3 from high to low percent immature bolls. Percent immature bolls at initial harvest aid application ranged from 65 to 90% (Table 1). In Exps. 1 and 2 Bollgard II Roundup Ready (Monsanto Co., St. Louis, MO) upland (*Gossypium hirsutum* L.) cultivar Sicot 71BR (CSIRO, Australia) was used while Exp. 3 used the non-transgenic upland cultivar Sicot 71 (CSIRO, Australia; Reid, 2003), the recurrent parent of Sicot 71BR. All experiments used a randomized complete block design with four replications.

On the day of each respective treatment application, crop status measurements were taken, including a count of the number of mature and immature bolls to determine the percentage of immature bolls. Immature bolls were determined by assessing the color of the seed coats contained within the bolls; bolls with seed coats that were not dark were deemed immature (Brecke et al., 2001). Bange et al. (2010) discussed several measures of crop status (additionally % open bolls, % immature fiber mass, and nodes above cracked boll) and reported good relationships between them for this study. Percent immature bolls are presented herein because it was seen to best represent the differences in quality at harvest, and although not definitely proven, is thought to potentially be a more reliable plant status measure when crops are non-uniform in their maturity and when they contain fruiting gaps.

The micronaire of machine harvested fiber samples that had been ginned without lint cleaning, was determined using an Uster Technologies High Volume Instrument model 900. Additional samples were subjected to one passage of a SDL 'Shirley' Analyser Mk2 (to remove some trash and help homogenize samples), and then tested for maturity ratio using the CSIRO polarized light microscopy instrument SiroMat (Gordon and Phair, 2005; Long et al., 2010b), gravimetrically determined linear density (mtex) using the CSIRO Cottonscan instrument (Naylor and Purmalis, 2005; Abbott et al., 2010), and fiber diameter (ribbon width) (μm) using the CSIRO photometric laser based instrument Sirolan-Laserscan (Lynch and Michie, 1976; Lunney and Irvine, 1979; Charlton, 1995).

2.2. Yarn manufacture

Four 42 g samples of machine harvested ginned fiber were taken from each experimental unit. Each sample was separately carded twice and drawn once using a 'Shirley' miniature spinning plant card and draw frame (Platt brothers, England). The four miniature

drawn slivers were then drawn together once using a Trutzschler HSR 1000 draw frame. The resulting single sliver was converted into twisted roving using a Zinser 660 roving frame which was then spun into yarn using a Zinser 350 ring spinning frame. Draft and twist was optimized for each sample to deliver approximately a 20 tex yarn with a twist factor of αe 3.7 (792 turns per meter). One yarn bobbin per experimental unit was tested for quality parameters. Of theses numerous parameters, strength is regarded as the single most important attribute (Meredith et al., 1991; May and Taylor, 1998) and was determined using an Uster Tensorapid 3. To complement the fiber maturity and neps interactions described by Bange et al. (2010), yarn nep content was determined using an Uster tester 4-SX.

For one replicate bobbin of each of the earliest and latest treatments, multiple yarns were positioned in electrical heat shrink tubing. Heat was applied to the tubing before transverse cross sections were cut and the resulting samples mounted on stubs. Samples were carbon-coated and digital images were acquired of the sections of yarns using an Hitachi S4300SE/N field emission schottky scanning electron microscope operated at a 1.2 kV accelerating voltage.

Remaining spun yarns were waxed and wound but not cleared using a Schlafhorst 238RM winder.

2.3. Fabric production, dyeing and testing

Wound yarns were knitted with a metric cover factor of 1.54 $tex^{0.5}$ mm^{-1}, on a Lawson Hemphill 25.4 cm "10 inch" F.A.K. knitting machine.

Knitted fabric was scoured and dyed with Cibacron blue LS3R (1%) reactive dye. This dye was recommended by a commercial dye house as being appropriate for showing the effects of immature cotton fiber and was like that used by others for a similar purpose (Bel, 2004; Bradow and Bauer, 1998; Han et al., 1998). Reflectance colorimetric measurements were taken of fabrics using a Gretag Macbeth Color-Eye 7000A spectrophotometer. Three measurements were acquired per experimental unit. The appearance of dyed fabric samples were measured using the CIELAB color opponent dimensions *L*, *a* and *b*. Differences between treatment fabrics were assessed in terms of delta *E* (Δ*E*), which describes the mathematical distance between two colors e.g. (Eq. (1)):

$$\Delta E = \sqrt{(L_1 - L_2)^2 + (a_1 - a_2)^2 + (b_1 - b_2)^2} \quad (1)$$

where 1 is the latest treatment and 2 the subsequent earlier treatment of comparison within each experiment. Delta *E* values near or greater than one between any two fabrics were deemed as being significant on the basis of the monochromatic nature of the dyed samples and the fact that in industry the samples would be viewed side by side as adjacent bands in knitted fabric.

Dyed fabric samples were tested for mass per unit area via Australian Standard (AS) 2001.2.13, and for the determination of bursting force via AS2001.2.19 (Standards Association of Australia).

2.4. Data analysis

One way ANOVA for quality parameters were conducted for each experiment. To give an indication of differences between the three experiments, a separate ANOVA was undertaken utilizing the mean treatment values as replicates for each experiment. Least significant difference testing (5%) was used for means separation. ANOVA and regression comparison testing was conducted using Genstat 12 (Lawes Agricultural Trust, IACR, Rothamsted, UK). Regression modeling was conducted using Sigma Plot 10 (Systat Software, Inc., San Jose, CA).

Table 2
Quality parameters for 20 tex ring spun yarns; strength and neps for each of the three experiments.

Harvest aid treatment	Strength cN tex^{-1}	Neps +200%
Exp. 1		
1	14.7	327
2	15.1	371
3	14.2	383
4	13.2	383
5	15.1	344
6	13.8	319
7	13.6	358
8	15.0	344
Average	14.3	354
LSD (0.05)	2.2	54
Exp. 2		
1	14.1	412
2	14.8	368
3	14.8	411
4	13.5	339
5	14.8	349
6	14.1	370
7	14.3	344
8	13.5	366
Average	14.2	370
LSD (0.05)	2.3	130
Exp. 3		
1	17.6	549
2	17.4	550
3	16.5	464
4	17.2	414
5	18.2	364
6	16.4	436
Average	17.2	463
LSD (0.05)	2.5	182
LSD (0.05) Exps.	0.7***	49***

*** ANOVA was significant at the 0.001 level.

3. Results

3.1. Fiber

In each experiment the timing of application of harvest aid treatments affected the amount of secondary wall thickening of cotton fiber with earlier treatment applications causing harvested fiber to be lower in micronaire, maturity ratio, and linear density (Table 1). Ribbon width was not affected by the timing of application of harvest aids. Experiment 3 produced fiber that was lower in micronaire, maturity ratio, linear density and ribbon width, in comparison with Exps. 1 and 2, which did not differ (Table 1).

3.2. Yarn

Within experiments there was no significant differences measured for the effects of treatments on yarn strength and nep content (Table 2). There was however significant differences between experiments, with Exp. 3 producing yarns that were on average stronger by approximately 3 cN tex^{-1} units and higher in nep content by approximately 100 neps (Table 2).

3.3. Fabric

Earlier harvest aid application treatments resulted in fabric that was significantly a lighter hue of blue relative to yellow (*b* dimension) (Table 3). For Exps. 2 and 3 earlier treatments produced fabrics that were significantly lighter in shade (*L* dimension) and a stronger hue of red relative to green (*a* dimension). Delta *E* calculations utilizing all three color space dimensions to compare the latest treatments to the others, showed that earlier harvest aid treat-

Table 3
Quality parameters for dyed knitted fabrics for each experiment. Fabric appearance is reported as color dimensions lightness (L), redness (a), blueness (b), and delta E (ΔE) calculations relative to the latest treatments. Fabric strength is reported as the burst force (N) relative to fabric mass per area ($g\,m^{-2}$).

Harvest aid treatment	L	a	b	ΔE	Strength $N\,(g\,m^{-2})^{-1}$
Exp. 1					
1	44.30	−2.21	−27.91	1.10	2.18
2	44.53	−2.26	−28.02	1.29	2.20
3	42.62	−2.00	−28.37	0.68	2.20
4	43.03	−2.02	−28.34	0.28	2.06
5	43.49	−2.12	−28.26	0.21	2.19
6	42.38	−1.92	−28.58	0.96	2.18
7	42.57	−1.96	−28.56	0.77	2.14
8	43.29	−2.11	−28.34	0.00	2.29
Average	43.28	−2.07	−28.30		2.18
LSD (0.05)	1.79	0.28	0.32**		0.18
Exp. 2					
1	43.30	−2.31	−28.11	1.80	2.21
2	42.63	−2.22	−28.27	1.11	2.50
3	42.08	−2.10	−28.59	0.47	2.26
4	41.87	−2.08	−28.68	0.25	2.08
5	41.69	−2.01	−28.70	0.08	2.17
6	41.47	−1.99	−28.79	0.18	2.32
7	41.49	−2.00	−28.83	0.17	2.31
8	41.65	−2.04	−28.76	0.00	2.37
Average	42.02	−2.09	−28.59		2.28
LSD (0.05)	0.64***	0.15***	0.24***		0.32
Exp. 3					
1	53.50	−3.39	−25.24	2.59	2.62
2	53.89	−3.39	−24.97	3.05	2.79
3	52.54	−3.38	−25.50	1.61	2.73
4	52.04	−3.32	−25.77	1.04	2.63
5	51.63	−3.32	−26.09	0.54	2.47
6	51.13	−3.21	−26.26	0.00	2.45
Average	52.46	−3.33	−25.64		2.62
LSD (0.05)	0.49***	0.10*	0.30***		0.36
LSD (0.05) Exps.	0.92***	0.12***	0.37***		0.12***

* ANOVA was significant at the 0.05 level.
** ANOVA was significant at the 0.01 level.
*** ANOVA was significant at the 0.001 level.

ments were significantly different in appearance with these fabrics having ΔE values >1 (Table 3). Across experiments, the shade of fabrics (L) was darkest for Exp. 2 and yet markedly lighter on average for fabrics from Exp. 3. Experiment 3 fabrics were more negative on the a dimension and more positive on the b dimension in comparison to Exps. 1 and 2 which were not significantly different (Table 3).

For fabric strength, there was no significant difference among treatments for the three experiments. However across experiments, fabric from Exp. 3 was stronger than fabric produced from Exps. 1 and 2 which were not different to each other (Table 3).

4. Discussion

4.1. Fiber maturity

The effect of defoliation timing on fiber maturity within and across experiments is evident in fiber cross section images (Fig. 1). Fibers from cotton harvested from the earliest treatments were less mature having thinner cell walls and appearing as flatter ribbons (Fig. 1b, d and f) in comparison to the later treatments for each respective experiment (Fig. 1a, c and e). Early defoliation arrested plant development, effectively terminating photosynthesis, and therefore prevented further cellulose deposition in fibers. Fibers from Exp. 3 appeared to have thinner cell walls for both early and late treatments when compared to the respective treatments for Exps. 1 and 2, corroborating the lower average micronaire, maturity ratio and linear density results for this experiment. As discussed in Bange et al. (2010) Exp. 3 was conducted during a markedly cooler season resulting in a delayed crop with more immature bolls and fiber; during the boll development period in each crop (February to April) Exp. 2 had the highest daily average temperature (24.5 °C) followed by Exp.1 (23.5 °C), while the coolest was Exp. 3 (21.3 °C).

4.2. Yarn performance

It was anticipated that the lower linear density of fiber from early treatments would contribute to stronger yarns due to more fibers in the yarn cross sections. However this was not the case for each of the experiments (Table 2). Early treatments had significantly shorter fiber (Bange et al., 2010) which may have negated any strengthening effects of more fibers in yarns. Additionally ribbon width was not different between treatments for the three experiments (Table 1), suggesting that there were no differences in the packing density of fibers in yarns. This was reflected in bundle strength results, with no differences present between treatments either (Bange et al., 2010). Between experiments however the less mature fiber from Exp. 3 produced stronger yarns. This fiber also tended to be longer than fiber from the other two experiments, and the ribbon width of this fiber was also smaller, reflecting the higher bundle strength results for this experiment (Bange et al., 2010). The smaller average ribbon width measured for fiber from Exp. 3 may be because this fiber had on average a smaller fiber perimeter, or it may have been due to lower fiber maturity which caused fibers to collapse more and fold up on themselves. Long et al. (2010a) showed that stronger yarns were manufactured from cotton varieties that although were lower in linear density and differed in maturity ratio, were only so when ribbon width was significantly

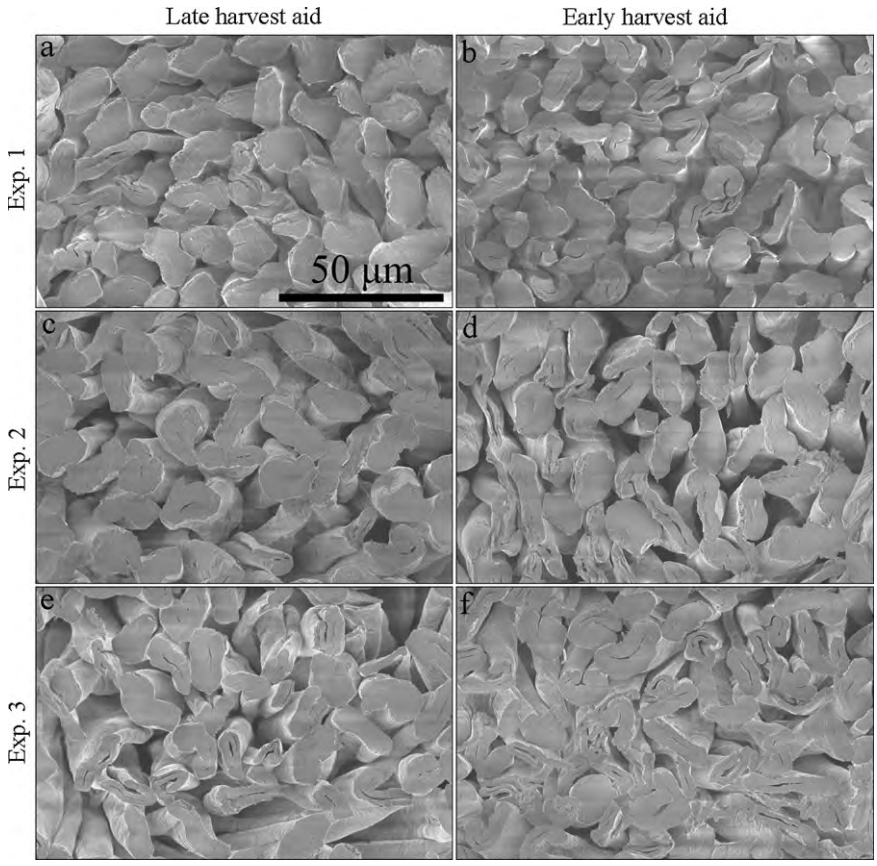

Fig. 1. Electron microscope images of cotton fiber cross sections from yarns spun for (a, c, e) late, and for (b, d, f) early harvest aid treatments from the three experiments.

smaller. Indeed there is an avenue for more in depth work examining the methods of measuring ribbon width, how ribbon width contributes to the mechanics of yarn strength, as well as how the factors maturity and perimeter affect ribbon width.

Although the level of fiber neps reported by Bange et al. (2010) were significantly greater for earlier harvest aid treatments, this did not translate into increases in yarn neps (Table 2). It is most likely that the two carding processes prior to spinning removed a significant proportion of these neps. In addition the samples used in this study were not lint cleaned so that the overall number of neps resulting from immature fiber was less prior to processing. The higher yarn nep content for Exp. 3 is attributed to the fiber from this experiment being markedly less mature and thus having a greater propensity to buckle and knot under the mechanical processing route (picking and ginning) even through lint cleaning was not implemented (Van der Sluijs and Hunter, 1999).

4.3. Fabric performance

Of the textile quality parameters measured, the timing of harvest aid treatments had the most significant effect on fabric color, which related well to differences measured in fiber maturity related attributes. Micronaire and linear density were equally good predictors, and both were better predictors than maturity ratio, of *L*, *a* and *b* fabric color dimensions for each of three experiments (Fig. 2). Likewise, Smith (1991) reported that secondary wall thickening maturity was not a complete measure of the dyeability of cotton, and that other factors including fineness and shape and the morphology of cellulose (which may well be related to fiber maturity) also influence dyeability. The same author also stated that micronaire had the highest correlations with dyeability.

These relationships between fiber maturity attributes and fabric color were typically experiment dependent, as exemplified by the linear regressions between micronaire or linear density and fabric redness dimension *a* (Fig. 2d and e), with slope and offset differences present between the three seasons with Exp. 3 being particularly different to the others. For the prediction of fabric lightness, Exps. 1 and 2 were more alike (Fig. 2a and b), while for fabric blueness Exps. 1 and 2 where in agreement with no offset differences (Fig. 2g and h). The slight varietal difference (conventional variety) and significantly cooler temperatures for Exp. 3 compared to the other two, most likely account for theses differences. Bradow and Bauer (1998) reported that genotype and temperature were significant factors affecting cotton dye uptake and stated that general environmental factors associated with decreased fiber maturity were linked to lighter colors in dyed fabrics.

Plant status measurements at the time of harvest aid application related well to changes in fabric color dimensions (relative to the latest treatments for each experiment) when the three experiments were assessed collectively. Changes in fabric lightness (Fig. 3a) and the degree of redness (Fig. 3b) were significantly related to % immature bolls ($R^2 = 0.81$ and 0.66 respectively). As expected the relationship between changes in the degree of fabric blueness and % immature bolls was stronger ($R^2 = 0.89$) (Fig. 3c), which was due to the blue dye used in this study. When the color dimensions were combined, ΔE values >1 (indicating distinct visual differences in fabric) occurred when there was more than 57% immature bolls. This equated to other closely related crop statuses, being when there was more than 48% immature fiber mass, more than 7 nodes above cracked boll, and when there was <26% open bolls at the time of treatment application (data not shown, see Bange et al., 2010). This work supports the current recommendation of applying harvest aids at greater than 60% open bolls (which

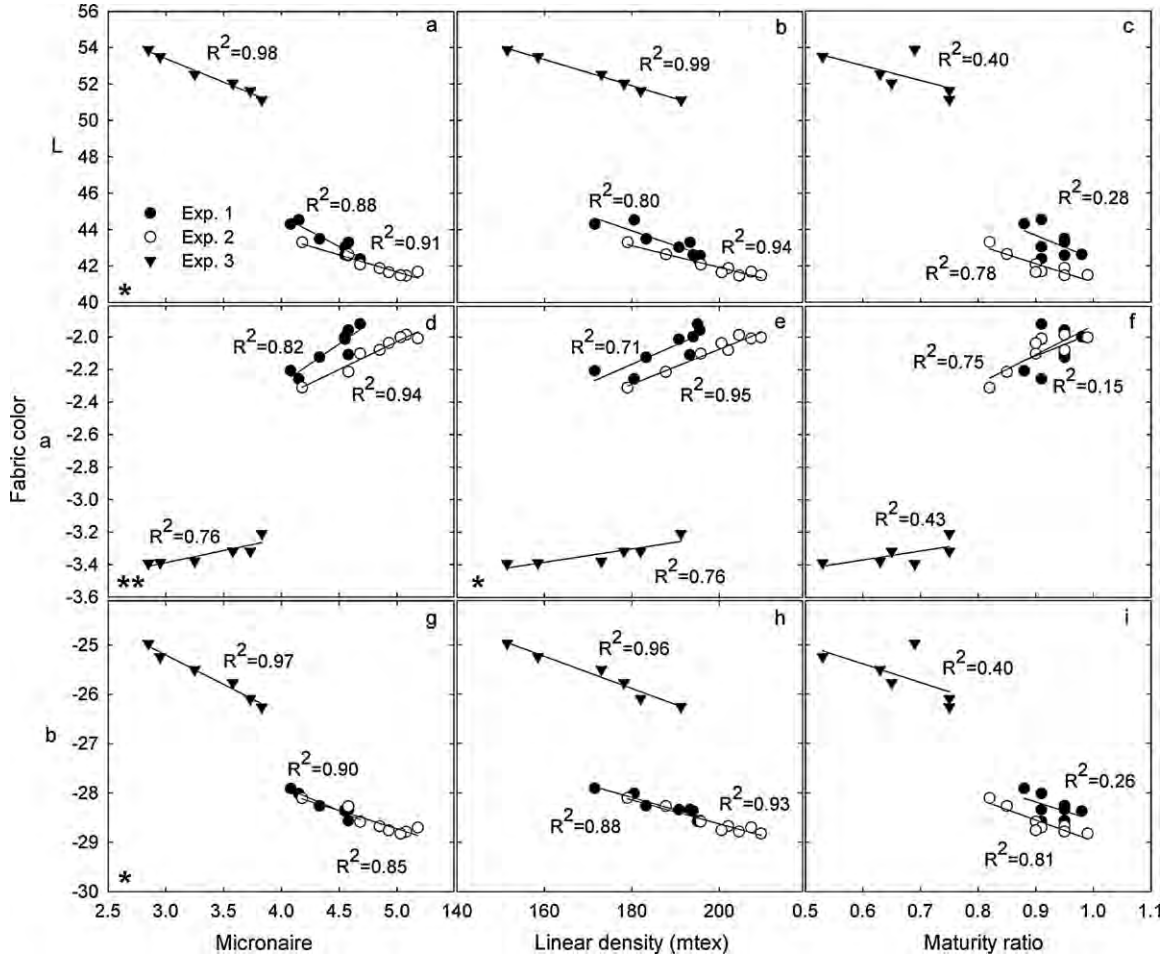

Fig. 2. Linear relationships between fiber maturity related attributes (micronaire, linear density and maturity ratio), and fabric color (dimensions *L*, *a* and *b*), for each experiment. For multiple regression analysis between the three experiments at each color dimension and fiber attribute combination, slope differences were reported at the 0.05 level (*) and at the 0.01 level (**).

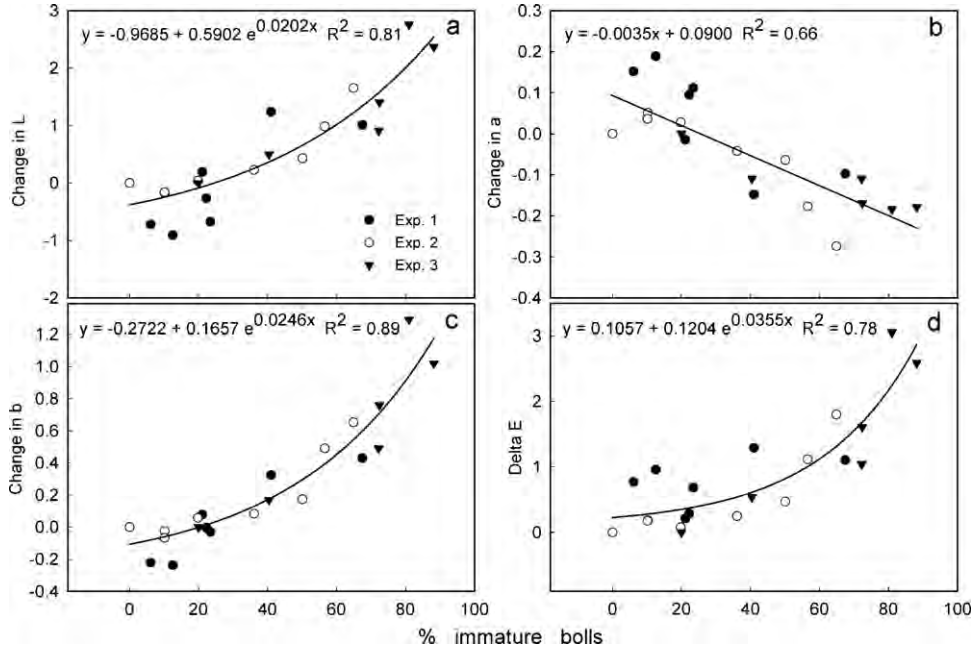

Fig. 3. Relationships between the plant status % immature bolls at the time of harvest aid application and the change in fabric color dimensions (a) *L*, (b) *a*, (c) *b* and (d) Delta *E*. The change in variable was calculated as the change in color from the latest harvest aid treatment for each experiment. Each regression is a three parameter exponential function ($y = ae^{(bx)} + c$), except for (b) which is a linear function ($y = mx + c$).

equates in this study to <29% immature bolls) (Snipes and Baskin, 1994).

5. Conclusion

Experiments were conducted that applied chemical harvest aids to upland cotton crops to manipulate the maturity of bolls and fibers. Earlier treatments produced less mature fiber that was lower in maturity ratio, linear density and micronaire. Yarn and fabric strength was not affected by treatments which was attributed to there being no changes in average ribbon width across treatments and thus with no influences in yarn packing density and inter-fiber friction. Fiber from earlier harvest aid treatments was also shorter which may have negated the strengthening effects of more finer (lower linear density) fibers in yarns. Less mature cotton from a cooler growing season produced stronger yarns and fabrics which was attributed to the smaller ribbon width and longer length of this fiber. Yarns made from this cotton had more neps because it was more prone to breakage and knot formation. Further studies are required to ascertain the influencing factors on ribbon width and the value that this fiber quality attribute may have on yarn mechanics. Micronaire and linear density related well to color space dimensions of dyed fabric, with these attributes better reflecting the specific surface area of fibers in fabric which significantly influence dye uptake and appearance. The percentage of immature bolls at the time of treatment application, as determined by the boll cutting method, related well to changes in color space dimensions (e.g. for fabric blueness b $R^2 = 0.89$). In this case harvest aids were employed to manipulate crop maturity. However other circumstances (e.g. production and weather related) will also influence maturity. Using the boll cutting technique to determine the status of a crop in the final stages of production (i.e. when harvest aids are implemented) will allow cotton producers to better understand how different production scenarios will affect crop maturity. Such information will also help the supply chain in general to preempt some of the processing performance issues of harvested fiber and improve fiber processing, e.g. ensure lay downs are more consistent.

Acknowledgement

Thanks to Jane Caton, Darin Hodgson, Mark Freijah, Fred Horne, Colin Brackley, Sue Horne, Margaret Pate and the CSIRO textile testing laboratory for technical assistance. We also thank Cotton Seed Distributors for provision of planting seed, and greatly acknowledge The Cotton Research and Development Corporation of Australia and the Cotton Catchment Communities Co-operative Research Center for their financial support. Much gratitude goes to the cotton producers of Australia for supporting research and development in their industry.

References

Abbott, A.M., Higgerson, G.J., Long, R.L., Lucas, S.R., Naylor, G.R.S., Tischler, C.R., Purmalis, M.M., 2010. An instrument for determining the average fiber linear density (fineness) of cotton lint samples. Textile Research Journal 80, 822–833.

Bange, M.P., Long, R.L., Constable, G.A., Gordon, S.G., 2010. Minimizing immature fiber and neps in upland cotton. Agronomy Journal 102, 781–789.

Bel, P.D., 2004 Cotton quality – fibre to fabric: fibre properties relationships to fabric quality. PhD Thesis. University of Southern Queensland, Toowoomba.

Bradow, J.M., Bauer, P.J., 1998. How genotype and temperature modify yarn properties and dye uptake. In: Proceedings of the world cotton research conference-2 , Athens, Greece. September 6–12, pp. 1070–1073.

Brecke, B.J., Banks, J.C., Cothren, J.T., 2001. Harvest-aid treatments: products and application timing. In: Supak, J.R., Snipes, C.E. (Eds.), Cotton Harvest Management: Use and Influence of Harvest Aids. The Cotton Foundation, Memphis, TN, pp. 119–143.

Cassman, K.G., Kerby, T.A., Roberts, B.A., Bryant, D.C., Higashi, S.L., 1990. Potassium nutrition effects on lint yield and fiber quality of acala cotton. Crop Science 30, 672–677.

Charlton, D., 1995. Sirolan-Laserscan. A review of its development, performance and application. Wool Technology and Sheep Breeding 43, 212–228.

Gordon, S.G., Phair, N.L.P., 2005. An investigation of the interference colors in mature and immature cotton fibers. In: Dugger, P., Richter, D. (Eds.), Proceedings: Beltwide Cotton Conferences. , pp. 2284–2290, National Cotton Council, New Orleans, LA.4-7 Jan. 2005. National Cotton Council, Cordova, TN.

Goswami, B.C., Martindale, J.G., Scardino FL, 1977. Textile Yarns – Technology, Structure, and Applications. John Wiley, New York.

Han, Y.J., Lambert, W.E., Bragg, C.K., 1998. White spec detection on dyed fabric using image analysis. The Journal of Cotton Science 2, 91–99.

Liakatas, A., Roussopoulos, D., Whittington, W.J., 1998. Controlled-temperature effects on cotton yield and fibre properties. Journal of Agricultural Science 130, 463–471.

Long, R.L., Bange, M.P., Gordon, S.G., van der Sluijs, M.H.J., Naylor, G.R.S., Constable, G.A., 2010a. Fiber quality and textile performance of some Australian cotton genotypes. Crop Science 50, 1509–1518.

Long, R.L., Bange, M.P., Gordon, S.G., Constable, G.A., 2010b. Measuring the maturity of developing cotton fibers using an automated polarized light microscopy technique. Textile Research Journal 80, 463–471.

Lunney, H.W.M., Irvine, P.A., 1979. Some factors affecting measurement by the CSIRO fiber-fineness distribution analyser. Textile Research Journal 49, 371–379.

Lynch, L.J., Michie, N.A., 1976. An instrument for the rapid automatic measurement of fiber fineness distribution. Textile Research Journal 46, 653–660.

May, O.L., Taylor, R.A., 1998. Breeding cottons with higher yarn tenacity. Textile Research Journal 68, 302–307.

Meredith, W.R., Culp, T.W., Robert, K.Q., Ruppenicker, G.F., Anthony, W.S., Williford, J.R., 1991. Determining future cotton variety fiber quality objectives. Textile Research Journal 61, 715–720.

Naylor, G.R.S., Purmalis, M., 2005. Update on Cottonscan: an instrument for rapid and direct measurement of fiber maturity and fineness. In: Proceedings: Beltwide Cotton Conferences ,. National Cotton Council, New Orleans, USA, pp. 2302–2306.

Reid, P.E., 2003. Sicot 71. Plant Varieties Journal. 16, 35–36.

Roberts, G.N., Constable, G.A., 2003. Impact of crop management on cotton crop maturity and yield. In: Proceedings of the 11th Australian Agronomy Conference , Geelong, VIC, http://www.regional.org.au/au/asa/2003/.

Smith, B., 1991. A review of the relationship of cotton maturity and dyeability. Textile Research Journal 61, 137–145.

Snipes, C.E., Baskin, C.C., 1994. Influence of early defoliation on cotton yield, seed quality, and fiber properties. Field Crops Research 37, 137–143.

Sullivan, R.R., 1942. A theoretical approach to the problem of yarn strength. Journal of Applied Physics 13, 157–167.

Van der Sluijs, M.H.J., Hunter, L., 1999. In: Layton, J.M. (Ed.), Neps in Cotton Lint. The Textile Institute, Manchester, UK, 24(4).